ENERGY TRANSACTIONS OF THE MULTIPAROUS DAIRY COW: DEVELOPMENT AND EVALUATION OF A MATHEMATICAL MODEL

By

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KEY TO ABBREVIATIONS

AA = amino acids
ADF = acid detergent fiber
AE_{mp} = available energy for milk production
BCS = body condition score
BE = body energy
BER = body energy reserves
BW = body weight
$BW^{.75}$ = metabolic BW
CF = crude fiber
CO2 = carbon dioxide
CP = crude protein
d = day
DIM = days in milk
DM = dry matter
DMD = dry matter digestibility
DMI = dry matter intake
EBF = empty body fat
EBP = empty body protein
EBW = empty body weight
EE = ether extract
ES = energy status
FCM = 4% fat-corrected milk
GE = gross energy
IE = intake energy
kf = efficiency of utilization of ME for growth and fattening
kf(l) = efficiency of utilization of BE for milk
kl = efficiency of utilization of ME for milk
km = efficiency of utilization of ME for maintenance
kp = efficiency of utilization of ME for pregnancy
LN = lactation number
ME = metabolizable energy
MIE = milk energy
mo = month
MPEe = mean prediction error of the equation
MPEm = mean prediction error of the model
MSEm = mean square error of the model

MSPEe = mean square prediction error of the equation
MTE = maintenance energy
MY = milk yield
NDF = neutral detergent acid
NE = net energy
NEI = net energy intake
NEL = net energy for lactation
NEm = net energy for maintenance
NSC = non-structural carbohydrates
PGE = pregnancy energy
qm = metabolizability of the diet
r^2 = coefficient of determination
r.e. = relative error
RE_{mp} = required energy for milk production
rsd = residual standard deviation
SBM = soybean meal
SC = structural carbohydrates
SCC = somatic cell count
SE = standard error
SNF = solids non fat
TBW = target body weight (BW at day prior to calving)
TDN = total digestible nutrients
TMR = total mixed ration
UADF = undigested ADF
UNDF = undigested NDF
VFA = volatile fatty acids
WCS = whole cottonseed
wk = week
WL = week of lactation
yr = year

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By

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The model developed in this study quantitatively represented dynamics of energy transactions of multiparous dairy cows over time. Intake energy (IE) was allocated to maintenance, lactation, energy reserves and pregnancy. The energy status (ES) was modeled. The model contained a differential equation representing body weight (BW) change and two algebraic equations representing IE and 4% fat-corrected milk production (FCMP). The three equations were interrelated and were solved simultaneously on a daily basis. Changes in BW resulted from energy deficits or surpluses. Intake energy was driven by energy requirements for maintenance, pregnancy and lactation, and by the energy required to attain a target body weight (TBW), defined as BW 1 d prepartum. Cows could produce to their potential (P) only when the amount of energy from feed and body reserves was equal or greater than that required. Otherwise, P was reduced to match available energy.

Parameters of the model were estimated simultaneously utilizing an implementation of the Nelder-Meade (1965) simplex algorithm. Three data sets were used to develop and evaluate the model. The number of cows, average FCMP and DMI of each data set were Monsanto (33 cows, 24.18 kg/d and 16.04 kg/d), NC-119 (89 cows, 28.73 kg/d and 18.79 kg/d) and Kodak (28 cows, 21.9 kg/d and 20.3 kg/d).

Capacity of the model to predict changes in IE, FCMP and BW with imposed successive reductions in dietary energy concentrations was evaluated qualitatively with each data set. Predicted responses of the model followed those expected in a real system. The model predicted increased DMI as a first attempt to maintain BW and MY; once an imposed DMI limit was reached, a decrease of BW was predicted. Thereafter, MY was predicted to decrease to the extent of the energy deficit.

The model was evaluated quantitatively by comparing actual and predicted DMI, FCMP and BW of two data sets using the parameters estimated from the third data set. Mean prediction errors (MPE_e) for DMI, BW and FCM ranged from 1.23 to 4.54 kg/d, 15.05 to 37.88 kg and .71 to .96 kg/d, respectively. These MPE_e values are indicative of acceptable predictive capacity compared with other models in the literature.

CHAPTER I
INTRODUCTION

In general, whereas both IE and secretion of energy in milk increase after calving, maximum IE is not reached until some weeks after maximal secretion of milk energy (MIE). Because of this lag in IE, body energy reserves (BER) are mobilized and the cow often loses appreciable amounts of BW. As lactation proceeds, and the partition of consumed energy moves towards body energy (BE) deposition, energy reserves are replenished and BW increases.

In past years there has been much interest in representing the bioenergetics of lactating and pregnant cows (Bywater and Dent,1976; Bruce et al., 1984; Williams et al., 1989a). However, no model available currently considers the dynamics of energy transactions among these concurrently occurring processes. Most current quantitative representations of these processes are static (no time frame). Furthermore, the available dynamic models do not consider the interrelationships of these processes simultaneously.

Understanding and quantifying the energy flow in a temporal and rate specific manner is essential in order to make decisions and control effectively the production and profitability of the dairy business. Continuously the dairy producer is faced with the problem of feeding cows to achieve optimum results. For this seemingly simple process, the dairy producer needs to be able to predict how milk production responds to IE, how IE affects body reserves status throughout lactation and the dry period. To accomplish this, it is critical to have a quantitatively organized representation of how energy is allocated by the cow for the competing processes of growth, lactation, maintenance, pregnancy and energy reserves mobilization or deposition.

The objective of this dissertation research was to develop a mathematical model that specifies the different energy transformations, and therefore the ES of the dairy cow temporally throughout the lactation-dry period cycle. Equations will describe how energy consumed is used to produce MIE and create BER, how BER are mobilized during early lactation to support milk production, and how MIE secretion rate and extent can affect IE (Figure 1-1).

The proposed model should allow the simulation of MIE, BE flux, and IE of lactating and nonlactating cows for any feasible rate of milk production. This information could be used to manipulate diets at any stage of lactation to influence milk yield (MY) and BE status. Some additional potential uses of the model are the following: a) predict future intake and feed energy requirements to aid the planing of economical production, purchasing and contracting of feed; b) determine the dietary energy costs associated with MY at any stage of lactation; c) develop nutritional strategies for the entire lactation by managing the cow's energy budget to maximize biological efficiency and economic benefits.

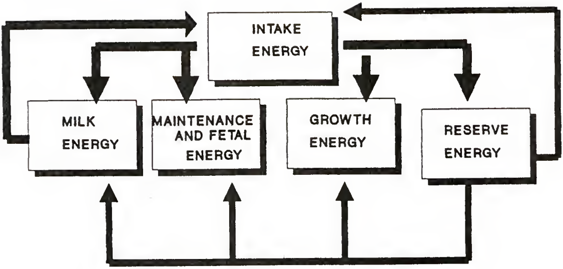

Figure 1-1. Diagram of the energy transactions occurring in the dairy cow

CHAPTER II
LITERATURE REVIEW

The first part of this literature review focuses on the biology and development of currently held concepts about energy transactions of the dairy cow. The last part of the review addresses mathematical models reported in the literature developed as quantitative representations of the biological transactions.

Partition of Energy Intake

At various stages of a cow's life cycle, certain tissues of the body demand metabolic priority over other tissues. Examples are metabolic requirements of the fetus and placenta during pregnancy, of the mammary gland during lactation, and of bone and muscle during growth. To accommodate the increased requirements of high-priority tissues, the cow must alter the pattern with which energy is partitioned among the tissues. The shift in energy partitioning occurs at several metabolic and physiological levels and is controlled largely by the central nervous system (Kennedy, 1967).

The partitioning of nutrients to various body tissues involves two types of regulation, homeostasis and homeorhesis. Homeostatic control involves maintenance of physiological equilibrium or constant conditions in the internal environment, such as regulation to maintain constancy of body temperature

(Bauman and Currie, 1980). Homeorhesis involves the orchestrated or coordinated changes in metabolism of body tissues to ensure a uniform flow of nutrients in support of a physiological state (Kennedy, 1967). As stated by Bauman and Currie (1980), probably the most pronounced example of homeorhesis would be in a dairy cow where initiation of lactation dramatically alters metabolism of many maternal organs in order that the mammary gland is supplied with nutrients necessary for synthesis of milk.

The gross energy (GE) from feed is the only exogenous means of introducing energy to the system. The observable outputs of the system are maintenance, pregnancy, growth, lactation, and body reserves.

Maintenance

Maintenance requirements are determined by a relationship with BW (NRC, 1989), previous nutritional status and amount of production (Jenkins and Ferrell, 1986), and tissue and external insulation relative to effective ambient temperature and other environmental conditions (NRC, 1981). Johnson (1986) found that maintenance requirements were related directly to effective ambient temperature.

Jenkins and Ferrell (1986) indicated that maintenance requirement was related directly to metabolic body size, which varies with organ tissues as a proportion of empty body weight (EBW). The NRC (1989) used the following equation to describe net energy requirements for maintenance (NEm) for dairy cattle:

$$\text{NEm (Mcal/d)} = .08 \times \text{BW}^{.75}$$

Maintenance energy requirements vary with physiological state, with more demanding physiological states having a greater requirement perhaps due to increased organ size as a result of lactation. Smith and Baldwin (1974) estimated that lactating cows have a 10% greater maintenance expenditure than nonlactating cows of similar BW. Canas et al. (1982) estimated a 24% increase in maintenance energy expenditure for lactation independent of increase in feed intake compared with the nonlactating state.

Variations in energy intakes above maintenance can be expected to change body tissue reserves which in turn influence maintenance energy (MTE) requirements of growing cattle and ER of cows. McCandlish and Gaessler (1920) found that fat animals required almost twice as much feed to maintain 100 lb (45.45 kg) of weight gained during fattening as to maintain 100 lb (45.45 kg) of weight gain during lean tissue accretion.

Growth

The amount of energy required by an animal for growth is equal to the total energy in the tissues gained. Total energy retention is a function of weight gain and energy concentration in the tissue that is deposited. Energy concentration in the deposited tissue is influenced by the rate of weight gain and its stage of growth or live weight (NRC, 1989).

Brody's function may be assumed to describe growth of animals (Taylor, 1968) so that

$$W = A\,[1 - e^{-k(t-t^{*})}]$$

Differentiating and substituting gives

$$dW/dt = -kW\log_e (W/A)$$

where growth rate (dW/dt) is decaying exponentially to zero as weight is maturing exponentially to an asymptotic mature weight (A).

Thus, the growth rate for mammals can be estimated if the mature weight (A) and the current weight (W) are known.

Pregnancy

Pregnancy includes the development of the fetus and growth of the fetal membranes, gravid uterus, and mammary gland. Because the total requirements for nutrients at the end of pregnancy are about 75% greater than those of a nonpregnant animal of the same weight, pregnancy is accorded a high priority in the partitioning of nutrients (Bauman and Currie, 1980). However, because the bulk of accumulation of fetal mass occurs in late pregnancy when the dairy cow is nonlactating, little competition exists between energy and nutrient use for lactation and the major phase of fetal growth. Competition by the fetus for nutrients that otherwise would be used for lactation or replenishment of protein and energy reserves would be increasingly important if dry-off was delayed to less than 60 d before expected calving (Moe and Tyrrell, 1971).

Lactation

The functional mammary gland is one of the most highly differentiated and metabolically active tissues in the body (Davis and Bauman, 1974). At the initiation of lactation, marked alterations in the general partitioning of nutrients and metabolism of the whole animal must occur to accommodate demands of the mammary gland. As pointed out by Brown (1969), the nutrient needs of the mammary gland are of such magnitude relative to total metabolism in a high producing dairy cow that the cow should be considered an appendage on the udder rather than the reverse.

One of the major changes occurs in adipose tissue, where the uptake of nutrients for synthesis of storage lipids is decreased, and lipid reserves are mobilized instead. Another key nutrient is glucose; the maximally-secreting mammary gland may require up to 80% of the total daily glucose turnover. To meet this need, rates of gluconeogenesis by the liver are increased dramatically, and presumably glycogen is mobilized (Davis and Bauman, 1974). A portion of the increase in liver gluconeogenic rates is from increased intake when lactation starts (Lindsay, 1971), but total glucose synthesized per day increases even if a constant feed intake is maintained as shown by Bennik et al. (1972).

The preference of other body tissues for nutrients to be oxidized for energy also is altered to allow partitioning of a greater percentage of glucose to the mammary gland. At d 30 prepartum, 34% of the total glucose turnover is oxidized to CO_2, whereas this decreases to only 8 to 9% by d 7 of lactation (Bennik et al., 1972). Nitrogen balance studies have demonstrated the importance of labile protein reserves in meeting amino acid (AA) needs for milk protein and glucose synthesis in early lactation. These reserves are substantial and may comprise 25 to 27% of total body protein of a dairy cow (Botts et al., 1979).

Many factors cause MY to vary both among animals and in the same animal at different times. Among animal variation is the result of differences in genetic potential, management, environment and nutrition. Factors which may influence MY of an individual cow include age, stage of lactation, pregnancy, rate of feed intake and allocation of feed over time (Bywater, 1976).

The yield attained in early lactation is dependent firstly on the genetic potential of the cow and is then a function of the quantity of energy available at the time. The quantity of energy converted into milk is influenced by the quantity of energy going into or out of body stores. During early lactation there are often considerable losses of BW as mobilized energy, to satisfy the increased demands of milk synthesis.

Body weight has an important curvilinear relationship to milk production. As BW increased so did MY, but to a point where optimum MY was reached (Brown et al., 1977). Milk yield decreased as length of lactation increased but day in lactation was found to be less important in predicting MY than other variables (Brown et al., 1977).

Crude protein (CP) content of the diet also was shown by Brown et al. (1977) to have an important curvilinear influence on MY, with maximum MY associated with 16% CP diets. These authors suggested that declines in production could be due partially to actual changes in utilization of protein as AA, and (or) to secondary effects associated with decreased feed intake.

Results of 20 experiments at the University of Florida (Briceno et al., 1988) with Holstein cows in early and mid-lactation showed that intake of protein (kg/d) expressed as CP, undegraded protein, and metabolizable protein explained 17.2, 20.9 and 23.5% of residual variation in MY and therefore, had more effect on MY than protein percent of the diet which explained only .6, 2.1 and 1.7% of variation. Medium-producing cows (MY > 22.8 kg/d) responded more to increasing protein intake than did lower producing cows (MY < 22.8 kg/d).

A high yield of milk during early lactation may be achieved either through a sufficient supply of dietary energy and nutrients at the time, or through the mobilization of body reserves resulting from a high plane of nutrition prior to parturition. The rate at which MY declines after the time of peak yield varies with cow and parity, but does not seem to be affected by the amount of yield at peak for cows of the same parity (Broster, 1972).

Body Energy Reserves

Body energy reserves are predominantly in the form of lipids stored in adipose tissue. The adipocyte has only two major functions, synthesis and mobilization of lipids. Because these processes tend to be reciprocal, their regulation is coordinated, and factors which directly affect one process tend to cause a reciprocal change in the other process either via direct or indirect action (Bauman, 1976).

Moe (1965) showed that during the first trimester of lactation, high producing cows (average production of 907 kg of FCM during the first 28 d of lactation) were in a negative ES and were using body reserves to meet their energy needs for lactation.

In fact, a zero net ES was not achieved until the point in lactation where milk production had decreased to less than 80% of peak production. During the first 10 wk of lactation the NE deficit was equivalent energetically to an average daily production of 9 kg of milk. Even more impressive, during the first month of lactation the body reserves being utilized (i.e., NE deficit) were equivalent energetically to about 33% of the milk produced.

Belyea et al. (1978) measured body composition changes across a lactation-gestation cycle of Holstein cows. Although composition of tissue lost during the first 2 mo postpartum (44.7% fat and 13.8% protein) was very similar qualitatively to the tissue gained during the last 2 mo prepartum period (44.9% fat and 13.8% protein), the quantitative losses following parturition (108 kg of BW, 48.4 kg of fat, and 14.9 kg of protein) greatly exceeded gains during late gestation (36.3 kg of BW, 16.3 kg of fat and 5.0 kg of protein). Because the fetus and placenta probably would contain only 4 to 6 kg of fat at parturition, there is a large apparent loss of maternal fat of about 42 to 44 kg in the early postpartum period.

For 9.3 Mcal/kg of fat and .75 conversion to MIE (NRC, 1989), this fat loss would yield about 20 Mcal NE/d during the first 14 d ((42 x 9.3 x .75) / 14) after parturition. For the cows in this trial which averaged about 600 kg of BW and 32 kg/d of MY during the first 14 wk of lactation, the total energy requirement averaged about 34 Mcal NE/d. If feed intake averaged about 2.7% of BW during this time, NE intake would be about 16 Mcal NE/d. About 18 Mcal NEL/d would be needed for zero net ES, which is similar to the 20 Mcal NE/d calculated from loss of body fat.

Body reserves may be mobilized during the first 6 to 12 wk postpartum, the length of this period depending on the genetic ability of the cow for milk production (Chigaru and Topps, 1981). The rate of mobilization tends to increase very sharply to a maximum at about 14 d postpartum (Trimberger et al., 1972) and approximately two-thirds of total body tissue mobilization occurs during the first 4 wk of lactation (Martin and Ehle, 1986; Trimberger et al., 1972).

Estimated rates of fat loss as high as 1.4 kg/d in early lactation were presented by Belyea et al. (1978) using the technique of whole body counting for K-40. Konig et al. (1979) used measurements of venous palmitate flux to estimate triglyceride mobilization. These data suggested that, at parturition, the instantaneous rate of body fat mobilization may be as high as 2.9 kg/d. Direct measurements of target rates of fattening (or fat replenishment) for cows are not available, but biochemical considerations suggest they could be high.

In rats, during lactogenesis, lipoprotein lipase activity in adipose tissue decreases (Hamosh et al.,1970; Knopp et al., 1973), and both flux rates and activities of key enzymes in the regulation of de novo fatty acid synthesis begin decreasing rapidly (Fain and Scow, 1966; Knopp et al., 1973; McNamara and

Bauman, 1978). The net effect is that energy storage in adipose tissue is diminished. Consistent with the reciprocal relationship between deposition and degradation, rates of lipolysis are increased markedly during early lactation as evidenced by adipocyte metabolism and(or) concentrations of free fatty acids in blood (Knopp et al, 1973; Mainaoy, 1978).

Ruminants and other mammals have similar adaptations in lipid metabolism. Chillard et al. (1977, 1978), working with goats, demonstrated that both lipoprotein lipase (necessary for the uptake of preformed fatty acids) and acetyl CoA carboxylase (a regulatory enzyme in de novo synthesis of fatty acids) decreased in activity in adipose tissue during late pregnancy and remained low during lactation. Other researchers (Metz and van den Bergh, 1977; Sidhu and Emery, 1972; Swan, 1976) demonstrated the same increased rates of lipid mobilization and decreased rates of lipid synthesis in adipose tissue of cows in late pregnancy and early lactation.

Body Protein Reserves

The nutritional significance of protein reserves is primarily to provide a source of readily available AA to animals during protein deprivation or stress. In general, protein reserves have been divided into a highly labile fraction comprising approximately 5% of total body protein and total reserves which can be as great as 50% of body protein (Biddle et al., 1975). Thus, about 50% of body protein is unavailable for mobilization.

The cow must rely heavily on body stores of energy and protein for milk production during early lactation. Swick and Benevenga (1977) suggested that the breakdown of muscle protein to provide AA for production of milk protein is a mechanism of normal metabolic adaptation. Protein reserves also could be used for glucose (and thus lactose) synthesis because certain AA are glucogenic (e.g., about 12% of lactose in milk can come from AA; Hunter and Millson, 1964).

Reid et al. (1966b) estimated that the lactating cow (average MY = 8672 kg/305 d) can mobilize up to .36 kg/d of body protein to contribute to milk production, whereas the estimation of Botts et al. (1979) was .25 kg/d for cows producing 22 to 26.5 kg of milk/d. These researchers suggested that repletion of previously depleted body protein occurred at rates up to .79 kg/d.

Although Belyea et al. (1978) reported an average total loss of maternal body protein during the first 2 mo postpartum of 9 to 10 kg (with an additional 6 to 7 kg of protein loss associated with the fetus), they emphasized that these losses in maternal protein were strikingly different among cows, ranging from 1 to 22 kg, and unrelated to MY as the cow with greatest loss (22 kg) produced less milk (6816 kg/yr) than higher producing cows (9546 kg/yr). Information on the total quantity of reserve protein is limited. Estimates have ranged from 5 to 40 kg of total reserve protein available to the lactating cow (Bull and Tamplin, 1975; Coppock et al., 1968). Paquay et al. (1972) measured a reserve of up to 17 kg of protein in the nonlactating cow.

Botts et al. (1979) measured protein reserves in a N depletion-repletion experiment with lactating Holstein cows. At the end of the depletion period, during which diets contained only 9% of CP, cows were assigned to diets containing 14, 18, or 22% CP. The groups were repleted for a period of 12.4, 9.6, and 7.4 wk and accumulated 14.6, 21.2, and 24.1 kg of protein, respectively. This represented 16.7, 25.1, and 27.1% of estimated total body protein if body protein represents 15% of BW.

Estimation of Energy Value of Body Reserves

Quantification of energy values of both body gain and body loss is important in developing models of energy transactions of the dairy cow.

Bath et al. (1965) measured the decrease in total BE of Holstein cows during the first lactation by two methods: carbon-nitrogen balance and comparative slaughter technique. They restricted feed intake to 65% of the minimum recommendation for 49 and 105 d to ensure considerable BW loss. Empty BW (EBW), instead of live weight, was used as an index of loss or gain in body tissue. During both periods EBW declined by 41 and 70 kg, respectively. The decrease in total BE amounted to a weighted mean value of 5 Mcal/kg shrunk BW loss. Results were not confounded by changes in gut-fill because estimations were from EBW.

The energy value of BW gains or losses depends upon the relative proportions of fat and protein in the tissues that are gained or lost. As these proportions change with increases in BW and stage of maturity, the energy values of tissues also change. The energy values used by NRC (1989) for body tissue gains and losses are based on an average energy value of 6 Mcal of body tissue energy/kg of live weight change, corresponding to a 600 kg cow; as such, these energy values over-estimate energy changes for lighter cows and under-estimate for heavier cows (Williams et al., 1989b; Table 2-1).

Table 2-1. Energy value of BW gain.

Live weight (kg)	Energy value of 1 kg BW gain (Mcal)[1]
450	4.92
500	5.59
550	5.65
600	6.00
650	6.35
700	6.70
750	7.04

Adapted from Williams et al. (1989b).
[1] Mcal = fat (kg) x 9.527 (Mcal/kg) + protein (kg) x 5.505 (Mcal/kg).

The ARC (1980) estimated the composition of gain as a function of EBW from data from about 600 animals covering wide ranges in breed type, sex, diet, and rate of growth using the equations:

$$\log_{10}\mathrm{EBP} = -.5037 + (.8893 \times \log_{10}\mathrm{EBW}) \qquad [1]$$

$$\log_{10}\mathrm{EBF} = -2.657 + (1.788 \times \log_{10}\mathrm{EBW}) \qquad [2]$$

where EBP is empty body protein (kg) and EBF is empty body fat (kg).

These equations then were transformed to their natural logarithmic forms and differentiated to obtain estimates of composition of BW gains at different EBW.

$$\ln(EBF) = -6.118 + (1.788 \times \ln(EBW))$$

$$EBF = e^{-6.118} \times EBW^{1.788}$$

$$dEBF/dEBW = 1.788e^{-6.188} \times EBW^{.788} \qquad [3]$$

$$\ln(EBP) = -1.1598 + (.8893 \times \ln(EBW))$$

$$EBP = e^{-1.1598} \times EBW^{.8893}$$

$$dEBP/dEBW = .8893e^{-1.1598} \times EBW^{-.1107} \qquad [4]$$

The EBW may be estimated from live BW by the following equation from ARC (1980):

$$EBW = (BW - 25)/1.09 \qquad [5]$$

$$Mcal = Fat\ (kg) \times 9.527\ (Mcal/kg) + Protein\ (kg) \times 5.505\ (Mcal/kg)$$

where 9.527 and 5.505 represent the heat of combustion values of fat and protein respectively.

Energy values for BW gains predicted with equations [3], [4], and [5] are in close agreement with values calculated by Reid and Robb (1971). The estimated energy value of BW gain for a 600 kg animal is 6.004 Mcal, which is almost the same as 6.0 Mcal/kg BW gain used by Moe and Tyrrell (1974).

These findings show that accurate estimates of the composition of weight gains of growing cattle can be obtained using the equations developed by ARC (1980), and this method can be used in development of mathematical models to predict production responses under different feeding regimens.

Reid and Robb (1971) also analyzed data that were representative of body tissue mobilization and deposition in lactating cows and found that weight gains and losses were higher when compared with those of steers, which were representative of body tissue gains due to growth. These data provide evidence that body tissue mobilized during early lactation has higher energy density than tissue gained under normal growth. It was concluded that the ARC (1980) equations do not give accurate results when used to predict the energy value of body tissue reserves of lactating cows (Williams et al., 1989b).

Comparison studies showed that more fat and less protein are lost per kilogram of tissue mobilized during early lactation when compared with amounts of fat and protein in tissue gained under normal growth as predicted with the ARC (1980) equations. The ratio of actual-to-predicted ranged from 2.17 to 1.37 for fat and from .35 to .70 for protein/kg of mobilized tissue. These results indicate that the tissues mobilized during early lactation have higher energy density than tissues gained under normal growth.

Fat and protein content of tissue gained by cows in late lactation were similar to those of tissue lost in early lactation. The ratio of actual to predicted gains ranged from 1.9 to 1.35 for fat and from .47 to .68 for protein/kg of tissue gained.

These findings suggest that the energy value of body reserve tissue mobilized and repleted at a particular live BW may be estimated by first predicting the composition of BW gain for that live weight using equations [3], [4], and [5], followed by adjustment using multiplicative factors to reflect the increased fat and decreased protein in this weight gain. The adjusted fat and protein, when multiplied by their energy densities, give the energy value of body tissue mobilized or repleted at the particular live weight.

$$\text{Mcal} = (\text{Fat (kg)} \times 1.4 \times 9.527\ (\text{Mcal/kg})) + (\text{Protein (kg)} \times .6 \times 5.5\ (\text{Mcal/kg})) \quad [6]$$

Multiplicative adjustment factors were calculated based on the observed-to-predicted ratios for fat and protein (Williams et al., 1989b). There seemed to be no definite relationship between live weight and these ratios, and as such, it was not possible to predict the adjustment factors from EBW. The highest correlations between calculated and predicted energy densities was obtained with a multiplicative factor of 1.4 for fat and .6 for protein.

Equation [6] was used to calculate the energy density for 1 kg of tissue reserves at different BW. These values are comparable with values reported (Flatt et al., 1965, 1967; Bath et al., 1965; and Moe et al., 1971). Cows weighing 550 kg had an energy value that approximated the value used by the NRC (1989) of 6 Mcal/kg. It is likely that rations formulated according to the NRC (1989) and fed to cows heavier than 550 kg will result in a low energy intake. Therefore, these cows will be unable to replete their energy reserves during late lactation, and will be in poor body condition when dried-off.

In practice many dairy producers manage energy reserves by observing body condition changes. Condition scoring systems have been developed for beef and dairy cattle in Europe and U.S. (Lowman et al., 1973; Wildman et al., 1982).

The advent of condition scoring allowed subjective assessment of subcutaneous fat cover by a simple, quick and repeatable method.

The body condition of a cow is assessed subjectively by visual appraisal and by feeling with the hand over the spinous processes of the loin area and around the tail head. A score of 1 to 5 (for the U.S. system) or 1 to 4 (for the European system) is given according to the ease with which the spinous processes can be felt and the amount of fat around the tail head. A condition score of 1 corresponds to an emaciated cow and a score of 5 (or 4 in the case of the European system) to an excessively fat cow.

In the study of Frood and Croxton (1978), low BCS at calving were associated with a low peak, low initial MY and high persistency, whereas a high BCS at calving was associated with an early peak, high initial MY and low persistency. A change in calving BCS was associated with 182 kg total yield, and an improvement in the first 2 mo of lactation equivalent to about 8% of total yield. The difference in peak and time of peak was attributed to differences in available body reserves at the time of low appetite and high energy demand. High scoring cows had body reserves available and could therefore achieve high MY at an early stage, low scoring cows had little or no body reserves and could not reach initial yields and did not peak until later, when appetite was increasing and sufficient dietary energy was available.

In their study, cows calving with a condition score above 2 (equivalent to 2.5 of the U.S. scoring system) produced more milk than predicted by the Herd

Management Control (HMC) technique (Milk Marketing Board, 1972), whereas those calving with a condition score below 2 produced less milk than predicted by that technique. The HMC technique to estimate total lactation yield uses a standardizing procedure, which makes adjustments for age, lactation number and season of calving based upon national average production, and in the case of multiparous cows, total yield in the previous lactation.

A study of Bouchier et al. (1987) of 1993 autumn-calving cows in 43 high yielding herds distributed throughout England and Wales found that MY over the first 12 wk of lactation was not affected significantly by condition score at calving when scores were above 2 (or 2.5 using the U.S. system). Garnsworthy and Jones (1987) reported that cows in fatter condition (BCS of 3.5 using the European system) at calving lost more weight over a longer period of time than cows calving in a thinner condition (BCS of 2). Those cows that were thinner at calving, had higher DMI than cows in fatter condition and produced proportionally more milk than did fatter cows, which relied more on depletion of body reserves to compensate for the lower intakes. Cows that were thinner at calving had a smaller interval between maximum MY and maximum DMI.

Land and Leaver (1980) found a positive relationship ($P < .05$) between MY and BCS over the first 8 wk of lactation, but Treacher et al. (1986) found a negative relationship ($P < .05$) between these variables over the first 6 wk. It can be concluded that the effect of BCS at calving on MY is variable and that other, yet unidentified factors, must be involved.

The effects of BCS at calving on milk composition generally are small and not significant (Frood and Croxton, 1978; Garnsworthy and Topps, 1982; Wright and Russell, 1984b; Garnsworthy and Jones, 1987). The general tendency is for cows with higher condition score at calving to produce milk with a higher milk fat content, but lower protein and lactose contents (Garnsworthy, 1988). This suggests that cows with high condition scores at calving have fat reserves that are more readily mobilized than their protein reserves and the lower protein content of their milk is a result of a more negative ES.

The rate of increase of feed intake and the time of maximum feed intake are affected also by the composition of the diet. The studies performed by Garnsworthy and Topps (1982) showed that as BCS at calving increased (from 1.75 to 3.57 using the European scoring system), the rate of increase in feed intake after calving decreased and the interval between time of peak MY and time of maximum feed intake became greater. Researchers agree that cows which are overly fat at calving have lower intakes of DM in early lactation (Garnsworthy and Topps, 1982).

Without exception, results of all studies conducted to investigate the effects of BCS at calving upon subsequent loss of body condition showed that the higher the BCS at calving the greater the loss of condition soon after calving. Cows calving with condition score below 2 (equivalent to 2.5 of the U.S. system) tended to gain condition.

In trials where condition scores were collected during a 6 mo or 2 yr period (Garnsworthy and Topps, 1982; Garnsworthy and Jones, 1987), BCS tended to converge to a value of 2.5 (equivalent to 2.9 of the U.S. system). Owen (1979) suggested that once cows have reached mature body size they have a target level of energy reserves which they try to maintain by physiological feedback mechanisms on energy intake. The convergence of BCS supports this hypothesis, but it is likely that 2.5 is only the average convergence point. The target may be different for individual cows, varying with genetic merit and the effects of the feedback mechanisms are probably modified by dietary and environmental conditions.

Being a subjective measurement, BCS could be criticized for not reflecting the true state of a cow's fat reserves. However, some workers have compared BCS with ultrasonic measurements and others with carcass composition. For example, Neilson et al. (1983) found correlations of .81 and .69 ($P < .001$) between BCS and backfat area measured over the 10th and 13th ribs and 3rd lumbar vertebra using a Danscanner. Using a Scanogram machine to measure fat depth over the 10th and 13th ribs, Garnsworthy and Topps (1882) found correlations of .589 and .761 ($P < .001$), and Garnsworthy and Jones (1987) found correlations of .589 and .603 ($P < .001$) between fat depth and BCS. A regression analysis yielded the following equation:

$$\text{Fat depth (mm)} = -2.421 + (1.874 \times \text{BCS})$$

$$(\text{rsd} = .6,\ r^2 = .75)$$

All of these correlation coefficients were highly significant, which gives a degree of confidence in the condition scoring system, but the high levels of significance should be viewed with caution because BCS is a discrete variate with a limited number of values. Also, correlating a subjective measurement of body fat with an objective measure does not establish causality; the correlation coefficient shows association, not agreement.

From the data of Garnsworthy and Cole (1986), the following prediction equation of the total fat content of the carcass (g/kg) of culled Friesian cows was obtained:

$$49.4 + (38.3 \times \mathrm{BCS})$$

$$(\mathrm{rsd} = 26.03,\ r^2 = .414,\ P < .001)$$

This indicated that both BCS and fat depth determined ultrasonically were reliable assessors of body fat content. Besides, being able to compute body condition, change in BCS over time can be a valuable tool for managing energy reserves.

Further evidence to support the use of BCS as an estimator of body fat was presented by Waltner et al. (1992). Using 23 lactating Holstein cows having an average condition score of 2.47 (range from 1.3 to 3. using U.S. system), an average DIM of 197 (range from 43 to 471) and average 305 d MY in the current lactation of 9070 kg (range 6018 to 11704), these researchers showed that BCS or body fat could be estimated by fat cell size ($P < .05$) with SE of 4.6 and 5.54 kg of lipid, respectively. Thompson et al. (1983) reported that with beef breeds condition score was a better estimator of EBF ($r^2 = .44$, $P < .01$) than weight-to-height ratio, length, weight, height, or heart girth. However, none of these estimators were acceptable for estimating EBF of Angus-Holstein cows. The fact that Holstein cattle deposit a greater proportion of fat internally than do cattle of beef breeds could explain the inability of the estimators to account for a greater percentage of variation in EBF (Wright and Russell, 1984a).

Limited data are available from dissected animals, but Wright and Russell (1984b) showed that BCS (European system) offered a very inexpensive method of assessing body composition, particularly for body fat in Friesian cattle, with an acceptable degree of precision:

$$\text{Fat (kg)} = -71.1 + (84.2 \times \text{BCS})$$

$$(\text{rsd} = 26.9,\ r^2 = .869)$$

$$\text{Water (kg)} = 201 + (22.2 \times \text{BCS})$$

$$(\text{rsd} = 21.9,\ r^2 = .64)$$

$$\text{Protein (kg)} = 62.8 + (7.35 \times \text{BCS})$$

$$(\text{rsd} = .717,\ r^2 = .723)$$

$$\text{Energy (MJ)} = -129 + (3478 \times \text{BCS})$$

$$(\text{rsd} = 1165,\ r^2 = .858)$$

In addition, these authors concluded after comparing beef and dairy breeds that the differences between genotypes in the proportion of fat stored in the main depots of the body resulted in differences in the relationship between BCS and body fat. British Friesian cows had a higher proportion of their fat in the intra-abdominal depots and the lowest proportion of subcutaneous fat, resulting in them being fatter at any given BCS than cows of the beef genotype.

To determine the available energy reserves of a dairy cow, Fox (1991) used BCS and BW (Table 2-2). For example, a 1300 lb cow in condition score 3.5 will contribute 219 Mcal of tissue energy as that condition score is used up or will require 219 Mcal of energy available at the tissue to regain that BCS. The table reflects a reduction in BE content as BCS decreases, which accelerates when BCS drops below 3 (U.S. system) due to a reduction in body fat as a percentage of the weight loss. This table can be used to compute days for a BCS change to occur. Assuming the following relationships published by NRC (1989): efficiency of use of ME for milk production = .64; efficiency of use for energy reserves. If IE exceeds requirements, 1 Mcal of NEL will provide (1/.64) x .75 = 1.17 Mcal tissue energy. A 1300 lb cow at BCS 3 and consuming 3 Mcal/d in excess of requirements will move to a BCS 3.5 in 219/((3/.64) x .75) = 62 d.

Table 2-2. Energy reserves at different BCS as a function of BW.

	BCS								
	1	1+ to 2-	2	2+ to 3-	3	3+ to 4-	4	4+ to 5-	5
BW (lbs)	Mcal/BCS								
1000	0	133	145	155	167	167	168	169	170
1100	0	147	159	171	184	184	186	187	188
1200	0	160	174	187	200	201	203	204	205
1300	0	174	188	203	217	219	220	221	222
1400	0	187	202	218	234	236	237	238	239
1500	0	200	216	233	251	253	254	255	256

Efficiencies of Utilization of ME

ME Use for Maintenance

Blaxter (1962) showed that in both sheep and cattle efficiency of utilization of ME for maintenance (km) averaged .83 and that the between-animal variation expressed as a coefficient of variation was ± 8%. Armstrong (1964) and Blaxter and Wainman (1964) later found that this efficiency was not constant; it tended to increase slightly with improving quality of the diet as exemplified by its metabolizability (qm = ME/GE), and there were real differences among broad classes of diets. ARC (1980) estimated km with the following equation:

$$km = .35\ qm + .503.$$

ME Use for Growth and Fattening

Whereas, in the mature cow the energy retained as fat varies from 85 to 95 % of total energy retention, in some young animals fat retention may account for as little as 50% of the retained energy. Breirem and Homb (1972) showed that efficiency of protein deposition of nonruminants or infant ruminants was only about .45. Rattray et al. (1974) reported efficiency values of .845 with a coefficient of variation of ± .291 for fat and .123 ± .023 for protein. These results suggest that there would be large differences in the efficiency of utilization of energy for growth as contrasted with fattening in ruminants.

However, Blaxter et al. (1966) showed that there were no differences in the values of efficiency of utilization of ME for growth and fattening (kf) obtained with growing Ayrshire bulls of 15 to 81 wk of age and 70 to 290 kg of fasted BW. The energy deposited as protein in the total energy gain varied only slightly from 32 to 25% as the bulls grew. Studies by van Es et al. (1969) with veal calves showed that energy retained as protein fell from 40 to 25% of total retention as the animals grew. No evidence of difference in kf was found in younger calves; overall efficiency of utilization was .69, very little difference in values was found with other species. Had protein been the substrate for growth, kf would be expected to be .60 (van Es, 1969). These results suggest that no great error is incurred when values for kf obtained in sexually mature animals are applied to younger ruminants in the growing stage and consuming fibrous diets. For calves subsisting on milk or milk replacers, kf is higher than in ruminating animals (ARC, 1980).

ME Use for Pregnancy

Studies with sheep by Robinson et al. (1980) showed that when the maternal body is not depleted, the efficiency of utilization of ME for growth of the fetus (kp) averaged about .13. The calculation entailed dividing the accretion in the uterus (determined by comparative slaughter methods) by the amount of ME consumed above maintenance of the nonpregnant animal. The results also permitted estimation of efficiency when maternal tissues alone were the source of energy for fetal growth. In this case, kp was slightly higher, that is .18. Graham

(1964) suggested that the low kp was due to the very high cost of maintenance of the fetus, placenta and fluids.

ME Use for Lactation

Results of extensive balance trials showed that kl was independent of amount of MY, stage of lactation, and breed (Flatt et al., 1969; Moe and Tyrrell, 1974), but dependent on composition of the diet (Moe et al., 1972; van Es et al., 1970) and milk composition (Tyrrell and Moe, 1972). Regression analysis of the results of 350 experiments with lactating cows by Moe et al. (1970) showed that kl was .644, and kf was .727. When the cows were not lactating kf was significantly lower (.596).

Van Es et al. (1970) concluded from their energy balance trials that kl averaged .60 for diets of 56.4% ME and that the efficiency increased or decreased by .0024 as the concentration of ME was increased or decreased by 1 percentage unit. Studies conducted by Moe and Tyrrell (1972) indicated that kl ranged from .61 to .64 as the ME content of the diet varied from 2 to 3 Mcal/kg DM.

According to results obtained by Moe and Flatt (1969) the efficiency of utilization of BE for milk secretion is about .84 ± .02. The value used by the NRC (1989) is similar, .82. Therefore, the efficiency of direct conversion of feed into milk is only fractionally greater than the efficiency of conversion of feed into body tissue and then into milk (kf(l = .727 x .84 = .61)) (.64 vs. .61, respectively). This means that the extra energetic cost of producing milk from body tissue is small, provided the tissue is deposited during lactation. Results of calorimetric studies (Blaxter, 1962; Armstrong et al., 1964; Moe et al., 1972) also have shown that whereas nonlactating animals use ME for maintenance and body gain with different efficiencies, lactating animals use ME with a similar degree of efficiency for both mintenance and gain.

Review of Proposed Models in the Literature

Feed Intake Models

Control and restrictions of feed intake, whether due to chemical and physical characteristics of the feed or the anatomy and physiology of the cow, represent one of the most practical limitations on milk production. Furthermore, published research has shown a strong correlation between DMI and MY. As stated by Adolph (1947), feed intake is one of the best regulated functions by animals.

As described by Forbes (1988), the approaches to predicting intake can be classified as

(1) multiple regression equations derived from data from a limited number and range of experiments, and

(2) models built from several equations which describe underlying factors thought to control intake.

However, these categories are not defined clearly as a combined approach is also possible (Monteiro, 1972).

Empirical DMI Models

DMI equations based on animal factors. The Ministry of Agriculture, Fisheries and Food (MAFF, 1975) published one of the simplest equations used to predict total DMI by dairy cows (Table 2-3). Equations of this type were derived by empirical means from experience of researchers rather than by formal analysis of data. Neal et al. (1984) suggested that these equations have proved to be almost as good, if not as good, as more scientifically derived equations. Bines et al. (1977) included BW change (kg/d) in their DMI prediction equation (Table 2-3). The equation developed by the ARC (1980) used only BW, MY and stage of lactation to predict DMI (Table 2-3).

McCullough (1981) developed an intake prediction equation from several studies conducted in Georgia (Table 2-3). He used a quadratic term for FCM to predict intake. The NRC (1989) intake guideline is based upon a linear relationship between 4% FCM and BW (Table 2-3). This equation was developed from research reports with cows producing 10 to 28 kg of milk/d. A diet moisture content factor was used to decrease DMI for each 10% increase in moisture content of the feed above 50%. Also a factorial DMI depression factor (.82) was used for cows in early lactation.

Kertz et al. (1991) summarized 6 yr of data from the Purina Research Center herd in Gray Summit, Missouri, which encompassed 18 experiments to quantify relationships among DMI, DIM, BW and 4% FCM. The best overall (all parities) equation predicting DMI (kg/d) is represented in Table 2-3. Data were best fit when separate equations were developed for each week postpartum up to 5 wk (when BW and 4% FCM changed rapidly) and then for periods including 6 to 8, 9 to 13, and 14 to 20 wk (Table 2-3). The predicted DMI for primiparous cows was different ($P < .05$) from that for multiparous cows, but there was no difference among second and greater parity cows (Table 2-3). The DMI followed a similar pattern for both first and second or later parity cows with a slower rate of increase for first parity cows until wk 5. After wk 5, DMI for first parity cows averaged about 15% less than that of later parity cows. Body weight loss was greater for later parity cows and reached a low at wk 5 to 7. Body weight increased progressively until wk 18. By contrast, first parity cows reached their low BW at wk 4 and stayed at that BW until wk 12.

For later parity cows the energy deficit lasted for the first 15 wk of lactation. Total digestible nutrients (TDN) intake deficit was calculated to be 3.6 kg or 19% of requirement. After wk 15, intake was in excess of requirements. In contrast, energy intake by first parity cows equaled requirement at wk 13, maximum deficit was at wk 9 postpartum (5% of requirement), and the magnitude of the energy deficit was less than for later parity cows. Also, first parity cows consumed more TDN than required for BW and FCM production after wk 13, which may have been a reflection of their growth requirements in addition to replenishment of body condition.

Roseler (1994) constructed a set of simplified and comprehensive DMI prediction equations for lactating dairy cows fed highly digestible, energy dense diets. The simplified equations were based on BW at calving, milk protein yield and an early lactation lag adjustment factor was included (Table 2-3). The comprehensive DMI equations were based on BW, BW change, milk protein yield, days pregnant and early lactation lag adjustment factor (Table 2-3).

DMI equations based on animal and dietary factors. By multiple regression analysis Conrad et al. (1964) determined that digestibility, fecal DM/1,000 lb BW per d, and BW accounted for essentially all the variation in feed intake when diet digestibility was between 52 and 66% and diets were composed mostly of roughage. When DM digestibility of these diets varied from 67 to 80%, intake decreased with increasing digestibility. From this study the authors concluded that physical and physiological factors regulating feed intake change in importance with changing digestibility of diet. Body weight (reflecting roughage consuming capacity), undigested residue per unit of BW/d (reflecting rate of passage), and DM digestibility were the factors affecting intake at low digestibility diets. At higher digestibilities, DMI appeared to be dependent on metabolic body size, MY, and diet digestibility (Table 2-4).

Table 2-3. DMI prediction equations based on animal factors.

Source	Equation
MAFF, 1975	DMI = .025 BW + .1 MY for average producers DMI = .022 BW + .2 MY for high producers Definition DMI, kg/d = dry matter intake BW, kg = body weight MY, kg/d = milk yield
Bines et al., 1977	DMI = .16 MY ± 2.45 BWC + .011 BW + 4.25 Definition DMI, kg/d = dry matter intake BWC, kg/d = body weight change BW, kg = body weight
ARC, 1980	$DMI = [.135\ BW^{.75} + .2(M - Y_{5000}\{n\})]F$ Definition DMI, kg/d = dry matter intake BW, kg = body weight M, kg/d = milk yield $Y_{5000}\{n\}$, kg/d = average milk yield for lactation n with a total lactation yield of 5000 kg, as defined by Wood (1967) F = adjustment of intake according to month of lactation
McCullough, 1981	$DMI = -5.535 + .02158\ BW + .5111\ M - .0024M^2$ Definition DMI, kg/d = dry matter intake BW, kg = body weight M, kg/d = 4% FCM production

Table 2-3 (continued).

Source	Equation
NRC, 1989[1]	$DMI = ((-.293 + .37\ FCM + .0968\ BW^{.75}) - Moisture) \times Early$ Definition DMI, kg/d = dry matter intake FCM, kg/d = fat-corrected milk BW, kg = body weight Moisture = discount for each 10% increase in diet moisture content above 50%, BW x .002 Early = discount of intake for cows in early lactation, factor = .82
Kertz et al., 1991	$DMI = .008037\ BW + .3134\ FCM + .2286\ DIM + .002176 DIM^2 + .00000705\ DIM^3;\ r^2 = .64$ $DMI_1 = 13.08 + .1468\ FCM - .003912\ BW - 1.3\ LN$ $DMI_2 = 12.04 + .1951\ FCM - .001136\ BW - 1.3\ LN$ $DMI_3 = 10.89 + .2061\ FCM - .002867\ BW - 1.3\ LN$ $DMI_4 = 10.19 + .2365\ FCM - .004073\ BW - 1.3\ LN$ $DMI_5 = 9.32 + .3031\ FCM - .005115\ BW - 1.3\ LN$ $DMI_{6\text{ to }8} = 9.09 + .3090\ FCM - .005115\ BW - 1.3\ LN$ $DMI_{9\text{ to }13} = 7.43 + .3008\ FCM - .010060\ BW - 1.3\ LN$ $DMI_{14\text{ to }20} = 6.65 + .3428\ FCM - .105553\ BW - 1.3\ LN$ Definition DMI_n, kg/d = dry matter intake at week n post calving BW, kg = body weight FCM, kg/d = 4% fat-corrected milk DIM = day in milk LN = lactation number, if lactation=1, otherwise 0

[1] From Rayburn and Fox, 1993.

Table 2-3 (continued).

Source	Equation
Roseler, 1994	Primiparous: $\mathrm{DMI} = (4.6 + .011\ \mathrm{CBW} + 12.4\ \mathrm{MPY})\ \mathrm{LAG}$ $\mathrm{DMI} = (3.7 + .012\ \mathrm{BW} + .12\ \mathrm{BWC} + 12.2\ \mathrm{MPY} - .011\ \mathrm{DPRG})\ \mathrm{LAG}$ Multiparous: $\mathrm{DMI} = (8.4 + .006\ \mathrm{CBW} + 12.2\ \mathrm{MPY})\ \mathrm{LAG}$ $\mathrm{DMI} = .6 + .05\ \mathrm{BW} + .11\ \mathrm{BWC} + 10.4\ \mathrm{MPY} - .013\ \mathrm{DPRG} - .17\ \mathrm{WIM} + 4.59\ \mathrm{Log\ WIM}$ Definitions: DMI, kg/d = dry matter intake CBW, kg = calving body weight MPY, kg/d = milk protein yield LAG = early lactation lag adjustment factor BW, kg = body weight BWC, kg/wk = body weight change DPRG = days pregnant WIM = weeks in milk postcalving

The multiple regression model of Curran el al. (1970) was stratified by week of lactation and included BW, diet concentrate amount, roughage digestibility and MY (Table 2-4). Animal factors had more effect on DMI in early lactation, whereas feed factors were more significant later in lactation.

Brown et al. (1977) developed regression equations for DMI and MY from 492 lactating cows in 19 separate experiments. They reported that DMI was correlated to location, season (S), DIM, MY, fat percentage of milk, BW, and diet crude fiber (CF) concentration (Table 2-4).

Valdiveloo and Holmes (1979) gathered data from 385 cows in 26 experiments at five locations and produced several equations for predicting forage DMI; the equation which explained the most variation (72%) is shown in Table 2-4. Yungblut et al. (1981) included dietary ADF percent in addition to animal factors (Table 2-4). The authors found poor agreement between predicted and actual values in a field evaluation of intake equations on 19 dairy farms.

Rayburn and Fox (1993) computed DMI regression equations for high producing cows on high forage diets in early lactation ($DIM < 84$) and for cows beyond early lactation ($DIM \geq 84$). The DMI in early lactation was related to BW, DIM and 4% FCM, whereas DMI was related with BW, DIM, 4%FCM and ration NDF later in lactation (Table 2-4). Weiss (1991) developed an equation for DMI when gut fill is limiting and another equation for intake when energy restriction is present. Weiss model included an early lactation adjustment factor (Table 2-4).

Ruiz (1993) obtained highest relationships with DMI when dietary fiber or undigested fiber concentration, fiber intake capacity expressed as percent of BW, and BW were used as independent variables (Table 2-4). Fiber intake capacity was calculated from the relationships of fiber concentration to fiber intake. Fiber was described in this equation as either ADF, NDF, undigested ADF (UADF) or undigested NDF (UNDF). An adjustment factor, which increased fiber intake estimate by 1 standard deviation unit for every 4 kg increase in 4% FCM above 25 kg/d was included. The best predictions of DMI were obtained by equations based on linear relationships of ADF, NDF, and quadratic relationship of UNDF concentrations to fiber intake.

Mechanistic DMI Models

According to Mertens (1987), although simplified dynamic models can be used to describe current information about intake regulation and explain interactions among mechanisms, they are of limited use as predictive systems because they can not be worked backwards easily to obtain the diet and animal characteristics that match a desired amount of intake. On the other hand, static models based on the concepts of long-term intake regulation offer the potential for developing useful mathematical models for predicting intake.

Mertens (1985) developed a mathematical model that describes feed intake regulation based on the concepts presented by Conrad (1966). The physiological theory of intake regulation can be described by the following equation:

$$Ie = R/E$$

Thus, when energy content of the diet (E, Mcal/kg) and energy requirements of the animal (R, Mcal/d) are known, the expected intake (Ie, kg/d) can be calculated. This equation, however, is valid only when dietary energy content is adequate to cause physiological feedback stimuli to regulate intake. It over-predicts intake when the energy content of the diet is low.

Similarly, the physical limitation theory of intake regulation can be described mathematically by the ratio between the daily feed capacity (C, kg/d) and the fill

Table 2-4. DMI prediction equations based on animal and dietary factors.

Source	Equation
Conrad et al., 1964	For DM digestibility between 52 to 66%: $\log I = -5.29 - 1.53 \log D + 1.01 \log F + .99 \log BW$ For DM digestibility between 66 to 80%: $\log I = 1.48 - 1.19 \log D + .62 \log BW + .27 \log E$ Definition I,lbs = daily intake D, % = dry matter digested F, lbs/d = fecal output BW, lbs = body weight E = sum of chemical energy in milk and body protein
Curran et al., 1970	$OMI_{1\text{ to }4} = -16.9 + .33\,BWC + .73\,C + .64\,Dr - .33\,MY + .005\,MY^2$ $OMI_{5\text{ to }8} = 87.0 + .86\,C - 3.1\,Dr + .03Dr^2$ $OMI_{9\text{ to }12} = -18.8 + 1.5\,C + .40\,Dr + .37\,MY + .22\,MY * C$ $OMI_{13\text{ to }16} = -7.2 + .66\,C + .41\,Dr + .09\,MY$ Definition OMI_t, lb/d = organic matter intake of week t in milk BWC, lb/d = body weight change C, lb/d = concentrate OM Dr, % = roughage digestibility MY, lb/d = milk yield

Table 2-4 (continued).

Source	Equation
Brown et al., 1977	$\ln \text{DMI} = .519 \pm \text{LOC} \pm \text{SEA} - .000827\ \text{DIM} + .148 \ln \text{DIM} + .339 \ln \text{MY} + .099\ \text{FAT} + .000675\ \text{BW} + .018\ \text{CF} - .000557\ \text{CF}^2$ Definition DMI, kg/d = dry matter intake LOC = location adjuster SEA = season adjuster (for fall, winter = .04; for spring = -.004; for summer = -.037) DIM = days in milk MY, kg/d = milk yield FAT, kg/d = milk fat yield BW, kg = body weight CF, %DM = crude fiber
Valdiveloo and Holmes, 1979	$\text{DMI} = -4.14 + .43\ \text{C} + .015\ \text{BW} - .095\ \text{WL} + 4.04 \log \text{WL}$ Definition DMI, kg/d = dry matter intake C, kg/d = concentrate intake BW, kg = body weight WL = week of lactation
Yungblut et al., 1981	$\text{DMI} = 3.36 + .3395\ \text{LN} + .3362\ \text{MY} + .5282\ \text{FP} - .1061\ \text{ADF} + .0096\ \text{BW}$ Definition DMI, kg/d = dry matter intake LN = lactation number MY, kg/d = milk yield FP, % = milk fat ADF, %DM = acid detergent fiber of diet BW, kg = body weight

Table 2-4 (Continued).

Source	Equation
Rayburn and Fox, 1993	If DIM < 84: $DMI = .0177\,BW + .0749\,DIM + .281\,FCM$ If DIM ≥ 84 $DMI = .023\,BW + .201\,DIM + .286\,FCM - .0979\,NDF$ Definition DMI, kg/d = dry matter intake BW, kg = body weight DIM = days in milk FCM, kg/d = fat-corrected milk NDF, % = neutral detergent fiber
Weiss, 1991	$DMI_{gf} = .011\,BW / 1 - (DE / (4.1 + .1\,EE))$ $DMI_{er} = .011\,BW + \frac{(2\,(.08\,BW^{.75} + .74\,FCM + 5\,BWC)}{(4.1 + .1\,EE)}$ $C_{LS} = .679 - .009234\,LWn + .39268\log LWn$ Definition DMI_{gf}, kg/d = DMI when gut fill is limiting BW, kg = body weight DE, Mcal/kg = digestible energy content of the ration EE,% = ether extract content of the ration DMI_{er}, kg/d = DMI when energy restriction is present FCM, kg/d = 4% FCM BWC, kg/d = BW change C_{LS} = early lactation adjustment LWn = week of lactation
Ruiz, 1993	$DMI = BW\,[(FIBW + FCMF)/F]$ Definition DMI, kg/d = dry matter intake BW,kg = body weight FIBW, % = fiber intake capacity FCMF = correction factor based on FCM yield F, kg = dietary fiber (NDF, ADF) or undigested fiber (UNDF)

effect of the diet (F, fill units):

$$Ie = C/F$$

Once more, this equation is only valid when the fill effect of the diet is high. Diets with low fill effects result in over-estimation of intake.

To predict actual intake (I, kg/d), Mertens (1985) adjusted the expected intakes of either of these equations for cow's response to external stimuli (such as feed flavors, pH stress, disease) by means of a psychogenic multiplier ($M, \leq 1$) of the expected intake:

$$I = Ie \times M$$

Furthermore, to use these theoretical equations to predict DMI, both R and E must be expressed in the same units. Because NDF is highly related with the fill effect, Mertens (1985) proposed that daily fill capacity (C) and dietary fill (F) should be expressed in units of NDF. As a result of several experiments Mertens estimated a daily NDF intake for mature cows of 1.2 ± .1% of BW/d using diets that produced maximum daily MY.

Therefore, intake (kg DM/d) under physiological regulation can be expressed as the ratio between NEL requirements (NER, Mcal NEL/d) and dietary NEL concentration (NE, Mcal NEL/kg DM):

$$I = NER/NE$$

The physical limitation theory of intake can be expressed in terms of NDF intake capacity (NDFIC, kg NDF/d) and NDF content of the diet (NDF, kg NDF/kg DM):

$$I = NDFIC/NDF$$

Unique solutions can only be obtained by determination of the points where these two equations intersect. Because energy content and fill effects are related inversely, the two reciprocal equations always will intersect at a point that predicts maximum DMI for a given level of production (NER).

As pointed out by Williams et al.(1989a), although the model defined by Mertens represents a significant improvement over previous methods of predicting DMI, assuming that all NDF sources influence intake similarly fails to reflect differences in intake between legume and grass-based diets, or diets with high-NDF byproduct feeds, formulated at equal NDF contents. Another limitation of this model is that it predicts more or less constant intakes over the entire lactation by assuming a constant gut capacity; this is unlikely to be real.

Legume-based diets have higher intakes than grass-based diets even when formulated at equal NDF content due to the faster rate of fermentation and greater buffering capacity of legume cell walls (Van Soest et al., 1984). In addition, because legumes have higher hemicellulose plus cellulose-to-lignin ratios (Mertens, 1983), any adjustment factor for NDF quality should consider not only this ratio (RATIO), but also the fraction of NDF of forage in the total diet (A).

Williams et al. (1989a) modified Mertens' model by allowing gut capacity to vary through lactation, by allowing an increase in intake as the deficit in meeting metabolic needs increase, and by incorporating a factor to account for the differences in intake of grasses and legumes. For this purpose, they used the following equation to adjust for NDF quality:

$$ANDF = NDF + (.5 - NDFADJ),$$

and the additive adjustment factor (NDFADJ) was calculated as follows:

$$NDFADJ = A \times FNDF \times RATIO \times 1.33^{-A}$$

where FNDF is the fraction of NDF in the forage. In addition, these researchers added equations to Mertens' model to modify intake for body tissue mobilization and deposition (as discussed later in the energy transactions section of this chapter).

The model of Williams et al. (1989a) improved the prediction of DMI for different forage-based diets. However, it is reasonable to expect that the theoretical model of intake prediction can be improved by incorporating more quantitative information about the characteristics of NDF. Also, the rates of digestion, passage and particle size reduction suggest that kinetic characteristics should be included in the static theoretical model to solve for intake under a variety of steady-state conditions. Finally, because availability of CP is important in determining daily MY during early lactation, Williams et al. (1989a) recognized that their model could be modified further by including dietary protein fractions and protein pools.

The regression equations described above are static in nature and probably can be useful only under the conditions which the data were collected. However, these equations provided some understanding of some of the factors that control feed intake which were considered in the development of the proposed model. An important feature in the model of Kertz et al. (1992) which has not been regarded by most modelers is the differentiation between cows in their first, second, and later parities.

Both Mertens' (1985) and Williams' (1989a) models are based on sets of theoretical equations with little practical application. In addition, the physical limitation theory of intake regulation and therefore, the models based on this theory have been questioned. Ketelaars and Tolkamp (1992) pointed out that intake patterns do not match requirement patterns during pregnancy and lactation and that there is no convincing evidence that this discrepancy is caused by physical restriction.

In view of the relationships between the efficiency of ME utilization and intake, these authors believe that the causes of changes in DMI may be sought in changes in metabolic processes rather than gut fill. When Johnson and Combs (1992) replaced rumen contents with water-filled bladders, they detected no changes in DMI or milk production regardless of the diet or stage of lactation. Bladders had no effect on chewing time per kg NDF intake or mean reticular motility. Cows compensated for the inert rumen bulk by expanding ruminal volume and reducing ruminal retention time. Ruminal pH and acetate-to-propionate ratio were increased by the bladders. As pointed out by Ketelaars and Tolkamp (1992) these changes in ruminal concentrations of acetate and propionate could be responsible of the intake depression observed in some experiments.

Models that Predict DMI, MY and BW Responses

Static models

Using a combination of empirical and mechanistic approaches the Cornell Net Carbohydrate and Protein System was developed to predict cattle requirements and utilization of feed to meet requirements under widely varying conditions. The system was assembled from separate submodels (Fox et al., 1992).

In the first submodel, the ruminal microbial population is divided into those organisms that ferment SC and those that ferment NSC, with differences in maintenance requirements and growth rates developed for each (Russell et al., 1992). Another submodel of the system predicts rates of feedstuff degradation in the rumen, the passage rate of undegraded feed into the lower gut and the amount of ME and protein that is available to the animal (Sniffen et al., 1992). In a third submodel, net tissue or lactation requirements are predicted from common descriptions available in practice, including frame size, BW and BCS, milk composition and environmental conditions (Fox et al., 1992).

Dynamic models

As stated by Forbes (1988), regression equations are essentially static in that they are used normally to predict intake on one occasion. An equation could be used repeatedly with successive externally-supplied values for MY, BW and BW change to generate likely intakes throughout a lactation. However, ME intake predicted at one period of lactation could be used to predict the change in body reserves and MY during the subsequent period. In turn, these could be used to predict subsequent intake. Therefore, the need for a dynamic approach for the prediction of not only DMI, but also MY and BW change seems apparent.

An iterative model of voluntary feed intake was developed by Forbes (1977a) to study the likely interactions between physical and metabolic limitations, particularly in early lactation. This model is based on a series of simple relationships among variables which were established by analysis of experimental results. The independent variables were changed daily and new values calculated for the dependent variables, which in turn were treated as independent variables in other parts of the model. Hence, given a cow's MY potential for each day of lactation, and calculating its voluntary feed intake, BW change was estimated thus altering the maintenance requirement and MY for the following day.

In this model, the amount of 'physically controlled intake' (PI) was calculated daily, whereas the amount of 'metabolically controlled intake' (MI) was assumed to be the weight of feed necessary to supply the ME requirements of the animal as specified by ARC (1965), assuming the deposition of .5 kg of tissue/d (mainly fat; i.e., 20 MJ/kg). The PI and MI were compared and the lower value assigned to feed intake. If PI was lower, the energy deficit was made good by reducing weight gain or inducing weight loss (assuming that weight loss yields energy for milk secretion with an efficiency of .83).

Furthermore, the decrease in MY (Dy) below the potential MY (kg/d) was calculated as a function of the intake deficit (MI - PI) in kilograms and DM digestibility (DMD):

$$Dy = (.056MY - .21) \times (MI - PI) \times DDM/100$$

Intake was not allowed to change by more than 1.5%/d, unless depressed by physical limitations.

The beef animal model (Loewer et al., 1985) is a dynamic model composed of four major submodels which attempts to relate economics, energy, plant and animal growth factors. These submodels interact to do a daily analysis of the effects of changes in resources and management on the production of beef cattle.

The animal submodel is composed of body composition, heat transfer and thermodynamic relationships, intake and digestion, energy and nutrient priorities. Each of these sections are dependent on the others so that the feedback loops are capable of over-viewing how these sections function and interact. The availability of nutrients and energy as well as the environment are factors considered to influence the model, but not be influenced by it.

The body composition of the animal and the relationships among its components are used to determine physiological age and to predict changes in EBW as a function of diet and environment. Physiological advancement may be limited by either energy, protein or mineral availability above maintenance. Likewise, physiological development also could reverse direction if energy, protein, and (or) minerals availabilities are less than that required for maintenance.

Irrespective of the intake of these, the animal can not advance more than one physiological day. However, excess energy is converted to non-essential fat while excess protein (N) and minerals are stored to some maximum as a constant percentage above the essential level associated with the existing physiological advancement.

Intake of DM is initiated only by a sufficiently low blood energy level. However, eating will cease if physical fill is reached, blood energy levels are sufficiently high, or body temperature rises above normal. The rate of digestion influences each of these factors, and vice versa.

The logic concerning milk production is based on the assumption that either the genetic potential, demand for milk or one milk input ingredient will be limiting. The degree to which each of these components is available is dependent on the outflow rates of milk production. These rates are functions of the amount of stored material and energy, and nutrient priority. Milk production can not exceed the genetic potential and may be limited by demand for milk or availability of milk components.

The Cornell Net Carbohydrate and Protein System (Fox et al., 1992) as well as the beef animal model (Loewer et al., 1985) are detailed and comprehensive models which include mechanistic aspects of feed digestion and fermentation. The type and number of inputs required to run these complex models limit their use under field conditions.

Forbes' (1977a) iterative model of voluntary intake seems more appropriate for describing interactions among energy demanding processes. Independent variables change daily and therefore new values need to be calculated for the dependent variable (e.g., feed intake). The dependent variable, in turn, will be treated as an independent variable in other parts of the model.

Energy Transaction Models

A deterministic model was designed by Bruce et al. (1984) to represent the bioenergetics of lactating and pregnant cows. This model is based on the empirical nutrient recommendations of the ARC (1980), but includes the concepts of lactation and growth potentials to predict milk production and BW change. The Goempertz function as described by Taylor (1968), was used to represent the growth potential of cows of normal body composition. If daily gain is calculated to be greater than growth potential, then the model assumes that the excess energy is stored as fat. For growth less than or equal to the potential growth, the energy value of BW change is assumed constant at 26 MJ/kg (ARC, 1980). For additional fat deposition the energy value is higher (39.3 MJ/kg; ARC, 1980) to produce slightly less BW gain. As for growth, the idea of a potential was introduced in the model for milk production. Wood (1967) represented the milk potential.

In this model the energy is partitioned between lactation and growth according to the principle of equal deficits, whereby each potential is reduced by the same amount of energy during a shortage. In other words, if the ME intake is sufficient for both growth and lactation, the milk production will be equal to the potential and the growth process will utilize the rest of the ME. However, if there is insufficient IE to meet both potentials then MIE and maternal BE change will be reduced by equal energetic amounts below the potentials; the deficits are equal.

The efficiencies of utilization of ME applied in the model are those recommended by the ARC (1980). Within the model the growth of the conceptus is obligatory and is given equal priority with minimal metabolism. The model commits energy to the conceptus before milk or growth is considered. By assuming that a relationship between body changes and milk production exists independent of the energy balance, the author is assuming that energy reserves are mobilized during early lactation whether the cow is on a negative energy status or not. This is a valid theory, but not the one chosen for developing the model in the current study.

The model developed by Bruce et al. (1984) requires IE and the metabolizability of the diet as inputs and only predicts MY and BW responses. This model can be used to measure the effects of changes of food levels and patterns, of the size and genotype of the cow on milk production and BW. As opposed to the model of Bruce et al. (1984), the proposed model will predict IE simultaneously with MY and BW. All three variables will be interrelated. Bywater and Dent (1976) developed a model to predict production responses at a whole animal level. To accomplish this they considered factors concerned with the intake, digestion and absorption of nutrients; demands of energy for maintenance, gestation, growth and milk secretion; and nonnutritional factors concerned with the regulation of milk secretion in the mammary gland.

The authors considered that the central driving force of the system was milk synthesis and that the cow is a processing center to which the necessary inputs are made available for this processing. As in the model of Bruce et al. (1984), maintenance of the animal and requirements for fetal growth are deducted from the production pool of metabolites, the remaining of which is then available for milk synthesis and for the synthesis of body tissue.

The pattern of partition of metabolites between milk and body tissue synthesis is regulated by considering that all of the production pool is available for milk synthesis and that any remaining metabolites may then be used for tissue synthesis. The potential MY in any time period is defined independently and the requirement for this may or may not be met by the metabolites available.

In this model the control of feed intake and the rates of fermentation and digestion are influenced by factors such as nature and quality of the feed, present energy demand, reticuloruminal volume and microbial population. These factors give an estimate of the nutrients absorbed by the animal in each time period.

Because the nature of the metabolites entering the system may determine the products of the system and the efficiency with which they are produced, this model operates at two levels. A control level and a more detailed operational level concerned with the actual flows of metabolites within the system. The functions of the control level are to monitor the physiological state of the animal and to control the relationship between the actual performance achieved and the potential performance. Thus, the control level estimates the maximum level at which milk production and tissue synthesis can occur during each time interval. These maxima are transferred to the operational level in the form of nutrient demands for milk production and tissue synthesis and compared to the levels of available metabolites.

Because the nutrient demand for milk synthesis is satisfied before the demands involved in body tissue regulation, the quantity and proportion of metabolites remaining for tissue synthesis depend on the amounts used in milk synthesis. The partition of nutrients is determined, therefore, by the level of milk synthesis in each period. If the demand for any process is not satisfied in one time period, this may affect the estimate of that demand in a subsequent period, and medium-term effects of energy supply can be accounted for and "fed-back" in this way.

Thus, for a given cow, the yield during early lactation is a function of the amount of energy available from ingested nutrients and mobilized tissues (i.e., is a function of intake and body condition) whereas, in later lactation, the yield depends on both the available energy and a residual effect of earlier performance which is reflected in the present milk demand. The cow is likely to lose stored energy and weight during early lactation when the demand for milk synthesis is high and will have a response potential in later lactation which is dependent on events during this early period. As the demand for milk synthesis falls off during later lactation, nutrients likely are to be in excess of requirements and may be directed back to tissue synthesis so that the animal regains BW.

Two assumptions were made in setting up the potential MY for this model. The first was that there was some factor or factors which governed the inherent ability to secrete milk (represented in the model as available units of capacity); whereas, the second concerns the rate and pattern of secretion of each unit of capacity (defined in terms of weight of milk). Both the available units of capacity and the rate of secretion of each unit are not influenced by nutrition, they only define a maximum limit for the ability to secrete milk at any time.

However, the extent to which the available units of capacity actually are used in each case is determined by the nutrients available, and thus the potential MY is largely a reflection of the previous feeding. In other words, the concept of capacity regulates the amount of MY and the response to changes in feeding while the secretion rate governs the pattern of yield at each level of nutrition.

The model developed by Bywater and Dent is mechanistic as opposed to the proposed model which will be empirical. In general, mechanistic models are complex and have limited use under field conditions, where the type of inputs required are not available. The model of Bywater and Dent (1976) uses a mechanistic approach to specify milk potential, which is difficult to estimate and probably no better than using Wood's equation. In this model, milk synthesis has priority over body tissue throughout lactation. The same assumption will be made in the proposed model.

As part of an energy transaction model, Williams et al. (1989a) defined the mobilization of body reserve tissue based on the following constraints: 1) tissue mobilization ends on d 70 postpartum; 2) it is maximum on d 14 postpartum; and 3) 66% of total mobilization takes place in the first 4 wk postpartum. The following equation was developed to describe the potential amount of body reserves (INCMt) that the animal was capable of mobilizing on day t

$$\mathrm{INCMt} = (.23 \times t^{b} \times e^{-ct}) - |5 - t|/351$$

The values of the parameters b and c used in this equation were .74 and .48, respectively. Values of INCMt were converted to fractions of total and were used to describe a fixed rate of tissue mobilization from a variable pool size. This pool of reserve tissue represented the potential amount of reserves the cow was capable of mobilizing.

As pointed out by Moe (1965), 33% of the MIE output during the first 28 d of lactation was obtained from body reserve tissues for cows producing an average of 907 kg of FCM during this period. Using this information, Williams et al. (1989a) calculated the potential fraction of energy coming from body reserves during the first 28 d of lactation (RSEN28)

$$\mathrm{RSEN28} = .33 \times \mathrm{FCM28}/907$$

where FCM28 is kg of FCM produced in the first 28 d of lactation. The term FCM28/907 was used as a scaling factor so that if FCM28 is larger than 907, then RSEN would be greater than 33%. The potential amount of body reserves (RESPO) that the cow is capable of mobilizing during the first 70 d postpartum was then calculated:

$$\text{RESPO} = (\text{RSEN28} \times \text{FCM28} \times .74 * 1.5)/\text{ENRES}$$

where .74 is the energy value in Mcal NEL/kg 4% FCM, the factor 1.5 accounts for the fact that only 66% of total potential reserves is mobilized during the first 28 d of lactation, and ENRES is the energy value of body reserves in Mcal NEL/kg. This equation would account for very high producers having a much greater potential to mobilize body reserves than lower producers, due to the scaling factor FCM28/907 used in calculating RSEN28, and the fact that FCM28 is related positively with total lactation production. However, RESPO could be in error for cows that deviate in BW from the BW on the cows in the study of Moe (1965).

In this model, it was assumed that the cow has the ability to replenish the body reserves mobilized during early lactation before drying off. Whether or not this is actually achieved would depend primarily on the IE relative to protein intake and MY in mid and late lactation.

To predict the rates of body tissue deposition after the initial period of mobilization was completed and assuming balanced protein nutrition, Williams et al. (1989a) developed the following function

$$\text{INCD}_t = .23 \times (376 - t)^{.8} \times e^{-.012(376 - t)}$$

where INCD_t (kg/d) is the amount of body tissue from a predetermined amount, which is deposited on day t of lactation, and 376 - t restricts the process to the period from d 71 to 305 of lactation. The values of INCD_t were converted to fractions of total tissue deposition, and the total amount of body tissues mobilized was multiplied by these fractions to obtain the potential amount of tissue reserves which the cow was capable of depositing on any day from d 71 to 305 of lactation.

The amount of energy needed to deposit body tissue reserves on day t of lactation was calculated and added to the energy requirements of the cow. This added energy represented a potential for body tissue deposition which may not be achieved if energy intake is lower than energy requirements. This may happen with high NDF diets and the total body reserves mobilized during early lactation may not be replenished by d 305.

The equations used to model body tissue deposition were based on the assumptions that all tissue actually mobilized in early lactation is fully replenished by d 305 of the lactation (Williams et al., 1989a). If full replenishment of body tissue was not achieved by this time, then it was assumed that the cow was capable of replenishing the remainder at a constant rate, equal to rate on d 305 or during the dry period with an efficiency of utilization of energy for body tissue deposition of .595.

As opposed to the model of Bruce et al. (1984), where body reserves were mobilized prior to the determination of IE and the amount of energy available from the mobilized tissue was subtracted from the energy requirements, in the model of Williams et al. model (1989a) the daily ES was calculated after calculating the energy requirements and predicting IE. Body reserves were mobilized or deposited depending on whether the ES was negative or positive. When mobilization occurred, the energy from the mobilized tissues was added to the IE, and this total available energy was partitioned to maintenance and production. Because no experimental data to support the theory that body reserves are mobilized independently of ES could be found, the proposed model will assume that depletion or repletion of body reserves is dependent on ES.

Total energy requirements on day t were calculated by summing the requirements for maintenance, milk production, pregnancy, growth, and BE deposition. Maintenance requirements of 80 kcal/kg $BW^{.75}$ and 73 kcal/kg $BW^{.75}$ were used for lactating and dry cows, respectively. The potential MY by day of lactation was described by Wood's (1967) equation. The energy value in Mcal NEL of potential MY was calculated by converting the actual milk yield to 4% FCM and multiplying it by .74.

The requirements for pregnancy in terms of Mcal NEL/d of gestation were calculated with the equation of Moe and Tyrrell (1972):

$$MEpt = .576 \times e^{.0174t}$$

where MEpt is the ME (Mcal) required on day t of gestation. These energy values were converted to NEL values dividing by 1.55 (Moe et al., 1971). Potential average daily gain was predicted using the first derivative of the Bertalanaffy growth function:

$$DW/dt = 3\ k\ Wt\ (u_t^{-.33} - 1)$$

where Wt is BW on day t, u_t is the proportion of mature weight attained by day t (u_t = Wt/A, where A is mature weight), and k is a rate constant, which determines the spread of the curve along the time axis. Values for k of .0026, .0024, and

.0022 were used for mature weights of 600, 650, and 700 kg, respectively (Baker and Koops, 1978).

When IE was insufficient through physical limitations to meet energy requirements after d 70 postpartum, a priority factor was used to decrease milk production and the extra energy was diverted to growth and BER deposition. Waldo (1986) suggested that production is decreased and the physical limit is driven up by an energy deficit. Therefore, the priority factor (PRIOR) for the first parity cows was calculated as:

$$\text{PRIOR} = (1/(\text{LACLEN} - 70)) \times (\text{DIM} - 70)$$

where LACLEN is the length of the present lactation in days. This factor ranged from almost 0 on d 71 postpartum to 1 at drying off. For older cows with higher intake capacity, PRIOR was multiplied by .25. This model assumes that during the first 70 d of lactation cows always produce milk at their potential. In addition, the multiplicative factor used after d 70 is totally independent IE and BER level. The model of the present research will improve this fault by evaluating in a daily basis if the energy available for milk production (IE ± BER - MTE - PGE) is sufficient to meet the energy required to produce milk at the potential. When BER and IE are not enough, the potential MY will be reduced according to the availability of energy.

These calculations were done for each cow in the model on each day of the production cycle and from the IE the various production variables such as milk production, BW change and BE deposition were determined.

The model of Bruce et al. (1984) is based on not very realistic and even contradictory concepts of growth and milk yield potentials and equal deficits. By assuming that a relationship between body changes and milk production exists independent of the energy balance, the author is assuming that energy reserves are mobilized during early lactation whether the cow is on a negative energy status or not. This is a possibly valid theory, but not the one chosen for developing the model in the present research.

The model developed by Bywater and Dent (1976) includes aspects of feed digestion and fermentation and results in a mechanistic model. Mechanistic models are complex and provide insight into processes of digestion. They are helpful in identifying those processes which influence intake and digestion, as well as the areas where more research is necessary. However, these models have very limited use under farm conditions due to the quantity and type of inputs required, which typically are not available.

In addition, the "available units of capacity" and "rate of secretion of each unit" described by Bywater and Dent (1976) do not seem to be either practical nor realistic concepts. An interesting aspect of their model is that the response potential in later lactation is dependent on events during early lactation.

In the model of Williams (1989a) a set of equations was used to quantify mobilization and replenishment of body reserves. These equations are based on constraints such as that tissue mobilization ends on d 70 postpartum, it is maximal on d 14 postpartum and 66% of total mobilization occurs in the first 4 wk postpartum. These constraints, if valid, certainly do not apply to each and every cow, or even whole herds on average. In this model, Williams et al. (1989a) assumed that cows produce milk to their potential and that the energy from feed and body reserves is enough for this amount of production during the first 70 d of lactation. This may not always be the case.

The main objective of the present research is to develop a mathematical model that specifies the complete set of energy transactions and therefore the ES of the dairy cow in a temporal and rate specific manner. Based on this objective, the proposed model should allow the prediction of MY based on the availability of feed and body reserves energy, without assuming that this amount of energy is sufficient to produce milk at the potential.

In this model, maintenance and pregnancy have higher energy priority than milk synthesis or depletion or repletion of body reserves, and milk synthesis has higher priority in the use of the remaining IE over depletion or repletion of body reserves. Ultimately, the proposed model is intended to be part of a management tool box. Therefore, it should predict the outcomes at a whole animal level without attempting to describe the mechanics of the biochemical and physiological processes. The number of inputs required to use this model should be minimal and not limit its application under farm conditions.

By specifying the complete set of energy transactions in a set of equations and solving them simultaneously in a continuous time frame, the proposed model should improve the accuracy as well as the spectrum of prediction of outcomes compared to models currently available.

CHAPTER III
DEVELOPMENT OF THE MODEL AND PARAMETER ESTIMATION

Introduction

Energy status (ES) of the multiparous cow is defined as follows:

$$ES = IE - MTE - MIE - PGE \pm BE$$

Quantification of the energy transactions in a continuous manner is essential. Potentially any decision about feeding, culling and breeding of a cow is influenced by, and thus should be based on or related to, the ES of the cow.

The purpose of this research was to develop a mathematical model to represent quantitatively the energy transactions among maintenance, gestation, lactation, and body reserves which take place in the multiparous dairy cow throughout the lactation-dry period cycle, and therefore define the ES over time. The equations of the model represent how IE is used to produce MIE and create BER in late lactation, how BER are mobilized during early lactation to support milk production, and how MIE secretion rate and extent can affect IE.

The proposed model should allow the simulation of MIE yield, BE flux, and IE of lactating and nonlactating cows for any feasible rate of milk production. This information could be used to vary energy input (e.g., component manipulation of diet) at any stage of lactation to influence MY and body ES.

The proposed model is dynamic. The basis for using a dynamic as opposed to a static model was that the former should enable the modeler to trace impacts of previous and current changes in ES and management decisions on subsequent performance of the cow. This model was intended as a method of predicting outcomes at a whole animal level without attempting to describe the mechanics of the biochemical and physiological processes involved. As an empirical model it was formulated at the specified level of aggregation based upon input and output data gathered at that level of aggregation. Because the set of equations that comprise the model should have exact solutions, this model can be classified as a deterministic model.

For construction of the model, maintenance (as a function of BW) and PGE were considered as fixed requirements that had to be fulfilled each day and deducted initially from daily IE. Once these requirements were met, it was assumed that milk synthesis had higher priority in the use of the available energy than depletion or repletion of body reserves throughout lactation.

In this model, rate of IE was assumed to be driven biologically by maintenance, pregnancy and milk energy needs. A healthy, nutritionally well-managed multiparous cow tends to recover BW lost during early lactation by the end of lactation and (or) during the dry period. This implies a certain stability of absolute BW across successive lactations. In this model, the target BW (TBW) was defined as the BW of the cow just before parturition because this theoretically represents the maximum BW for any lactational cycle of a multiparous cow and includes BW associated with pregnancy. Because the proposed model was intended to be part of a management tool box, the difference between the current BW and the TBW were incorporated into the IE equation. Accordingly, the model predicts how much energy a nutritionally well-managed cow should consume. If a diet with high energy density is offered, the expected response would be a decrease in DMI rather than gain of excessive BW. On the other hand, feeding a diet of low NEL concentration should produce an increase in DMI.

In this model, growth was not considered among the metabolic processes. It was assumed that after the third calving, cows have achieved mature body size and changes in BW represent changes in fat content (e.g. body composition). Therefore, this model was developed from data and predicts responses for third and greater parity cows.

Materials and Methods

Experimental Data Sets

The Monsanto data set, collected at the University of Florida Dairy Research Unit (Hartnell et al., 1991), was used to develop the model. This data set included measurements from 33 multiparous Holstein cows. Mean MY for the entire lactation was 24.18 kg/d, with a maximum of 31.63 and a minimum of 9.7 kg/d; mean DMI was 16.04 kg/d, with a maximum of 18.0 and a minimum of 5.9 kg/d over a 336 d experimental period. Beginning 60 ± 3 d postpartum, cows received either 0, 250, 500 or 750 mg of n-methionyl bST (sometribove). Treatments were administered at 14-d intervals by subcutaneous injection.

Polynomial models were run and evaluated using SAS (1985) GLM procedures to characterize BW, DMI and FCM production responses. These models included treatment, cow(treatment) and DIM.

For the Monsanto data set, all dietary ingredients and TMR samples were analyzed at the Northeast Dairy Herd Improvement Laboratory (NEDHIA, Ithaca, NY). Diets were formulated to meet or exceed NRC (1989) requirements for all cows. Cows were housed in a freestall barn and fed TMR ad libitum individually through electronic gate feeders (American Calan, Northwood, New Hampshire). The ingredient and nutrient composition of TMR fed during the experiment varied according to stage of lactation. Cows which were in early lactation during the hot season (from June through September) were fed the early-hot diet, whereas those cows which were in early lactation during the cool season (from October through May) received the early-cool diet (Table 3-1). All cows received the late diet during late lactation.

Amount of feed consumed daily was monitored and calculated throughout lactation. Diets and ingredients were sampled weekly and composited monthly. Cows were milked and yield was recorded twice daily throughout lactation. Milk composition (fat, protein, lactose and SCC) was determined from samples collected weekly during two consecutive milkings. Cows were weighed for BW weekly after the a.m. milking throughout lactation.

Table 3-1 Ingredient and chemical composition of TMR fed to cows during the Monsanto trial conducted at the University of Florida.

	----------------------Diets------------------------------		
	Early-cool	Early-hot	Late
Item	------------------ % of dietary DM-------------------		
Alfalfa hay	13.3	13.0	25.0
Corn silage	34.2	33.0	49.2
Corn-cracked	16.0	15.7	6.2
Whole cotton seed	9.5	10.3	...
Distillers dried grain	13.1	13.7	8.4
Soybean meal[a]	10.8	10.8	9.7
Mineral supplement	3.1	3.5	1.5
CP	17.6	17.9	15.7
ADF	23.3	23.2	26.1
NDF	37.8	37.7	42.6
Lignin[b]	5.4	5.4	5.6
Ash[b]	7.5	7.9	6.4
EE[b]	5.5	5.7	3.1
NEL, Mcal/kg[c]	1.70	1.70	1.54

[a] 44% soybean meal.

[b] Values assigned from ingredient tables of Van Soest (1992) and weighted according to total dietary composition to compute percent of dietary DM.

[c] Calculated from individual ingredient composition.

A data set was provided by J. B. Holter from five different experiments conducted at the University of New Hampshire. Because the NH data set was generated from different experiments which comprised a variety of dietary treatments, the NH data set was split into three sets according to NEL concentration of the diets (Table 3-2).

Mean MY with high NEL concentration (referred to as high NH) was 29.90 kg/d (ranging from 14.63 to 41.86 kg/d), mean DMI was 19.12 kg/d (ranging from 15.05 to 21.48 kg/d), with medium NEL concentration (referred to as medium NH) mean MY was 29.23 kg/d (ranging from 13.36 to 41.68 kg/d) and mean DMI was 19.06 kg/d (ranging from 15.1 to 21.76 kg/d), mean MY with low NEL concentration (referred to as low NH) was 27.06 kg/d (ranging from 11.29 to 40.06 kg/d), mean DMI was 18.20 kg/d (ranging from 14.83 to 21.04 kg/d). The total range of the studies was 336 to 780 d.

Table 3-2. Average NEL concentrations of diets used in NH data set at different stages of lactation.

		Average NEL (Mcal/kg)		
Stage of lactation	DIM	HIGH	MEDIUM	LOW
Early	1 to 112	1.72	1.69	1.66
Mid	113 to 224	1.58	1.55	1.53
Late	> 224	1.57	1.52	1.51

The parameters of the model which will be discussed later in this chapter, were estimated only for the medium NH data set. The selection of this data set was based on the similarity between the dietary NEL concentrations of the Monsanto and the medium NH data sets.

Many of the same cows received different dietary treatments throughout the five experiments that comprised the NH data set. To avoid bias due to cow and treatment, both effects were included in the model. The polynomial models constructed to characterize BW, DMI and 4% FCM responses also included DIM, DIM^2, DIM^3, DIM^4, DIM^5 and DIM^6 and were run and evaluated using SAS (1985) GLM procedures.

The composition of the diets varied among experiments and were described in Holter et al. (1992, 1993, 1994). In all experiments, cows (n = 89) were fed and milked twice daily. Cows were housed in a conventional tie-stall barn with individual feed mangers and waterers, were fed some dietary components separately. Feeds were sampled every 2 wk and composited by 4-wk periods; and orts were sampled and composited by treatment every 4 wk. Each cow's BW was recorded prior to feeding and milking once every 2 wk. Weights of MY, diets offered and orts were recorded daily. Biweekly morning and afternoon composites of milk were analyzed for fat and SNF contents.

The Kodak data set was generated from a study conducted at the University of Florida (Otterby et al., 1990). This data set included measurements from 28 multiparous Holstein cows. Mean MY was 21.9 kg/d, with a maximum of 32.5 and a minimum of 13.2 kg/d; mean DMI was 20.3 kg/d, with a maximum of 24.2 and a minimum of 14.8 kg/d. Holstein cows were assigned to either a basal diet or one of four diets supplemented either with .4, .8, 1.2, or 1.6% ammonium salts of VFA, as a percent of dietary DM.

Polynomial models were run and evaluated using SAS (1985) GLM procedures to characterize BW, DMI and 4% FCM production responses. These models included treatment, cow(treatment) and DIM.

Cows were fed ad libitum TMR based on corn silage and either alfalfa silage or chopped alfalfa hay. Concentrate contained ground shelled corn or high moisture corn and soybean meal for supplemental protein. The forage-to-concentrate ratio was 50:50 during 1 to 112 DIM of lactation and changed to 60:40 and 70:30 for 113 to 224 DIM and 225 to 305 DIM, respectively. The compositions of the diets are shown in Table 3-3.

Daily feed offered and refused were recorded. Diets were sampled weekly, composited monthly, and analyzed for DM, CP and ADF. Milk yields were recorded at each of the two milkings daily. Every 14 d, milk was sampled at morning and afternoon milkings for composition analyses. Cows were weighed immediately after calving and at 2 wk intervals thereafter. Animals were housed in a freestall barn and fed individually through electronic gate feeders (American Calan, Northwood, New Hampshire. Dietary NEL concentration varied with stage of lactation (Table 3-3).

Proposed Model

The mathematical model was composed of a differential equation that represents daily BW change (Table 3-4) and two algebraic equations which represent daily IE and FCM (Table 3-5 and Table 3-6). The amount of energy required for maintenance, BW change and 4% FCM yield obtained in calorimetric studies (Moe et al., 1971; Moe et al., 1972; NRC, 1989) was represented in the

Table 3-3. Ingredient and chemical composition of diets used in Kodak trial at different intervals of lactation.

	Days of lactation		
Item	1 to 112	113 to 224	225 to 305
	--------------------------% of DM--------------------------		
Corn silage	37.50	45.00	52.5
Alfalfa hay	12.50	15.00	17.5
Ground shelled corn	35.43	28.34	21.26
Soybean meal[a]	11.77	9.42	7.062
Dicalcium phosphate[b]	.43	.34	.258
Limestone[c]	.78	.62	.468
Salt[d]	.56	.45	.34
Dynamate[e]	.35	.28	.21
CP	15.90	14.90	14.00
ADF	18.30	21.20	24.10
Ca	.79	.78	0.76
P	.44	.40	0.36
Mg	.20	.21	.23
K	1.11	1.16	1.21
NEL, Mcal/kg	1.71	1.69	1.66

[a] 54% CP, DM basis.
[b] Contained 20 to 22% Ca and 18.5% P.
[c] Contained 36 to 39% Ca.
[d] Trace mineralized salt.
[e] Contained 11% Mg, 22% S and 18% K.

model as α_2, α_3 and α_4, respectively. The dietary NEL concentration was represented in the model as α_1.

Table 3-4. Differential equation representing BW change in the proposed model.

$$\frac{dBW_t}{dt} = [IE_t - RE_t] / \alpha_4$$

$$= [IE_t - MTE_t - MIE_t - PGE_t] / \alpha_4$$

$$= [\alpha_1 \; DMI_t - \alpha_2 \; BW_t^{.75} - \alpha_3 \; FCM_t - PGE_t]/\alpha_4$$

Definition

$\frac{dBW_t}{dt}$, kg/d = body weight change for d t

IE_t, Mcal/d = intake energy at d t

RE_t, Mcal/d = required energy at d t

α_4, Mcal/kg = energy requirement for BW change (NRC, 1989)

$\alpha 1$, Mcal/kg DM = energy concentration of the diet

DMI_t, kg/d = dry matter intake at d t

α_2, Mcal/kg.75 = energy requirement for maintenance
= .08 Mcal/kg$^{.75}$ (NRC, 1989)

α_3, Mcal/kg = energy requirement for 4% FCM production (NRC, 1989)

FCM_t, kg/d = 4% FCM at d t
= (.4)(kg of milk) + (15)(kg of fat)

PGE_t, Mcal/d = pregnancy energy at d t (ARC,1980)
= $[10\text{^}(151.665 - 151.64 \; e^{(-.0000576 \; tp)})] \; .133/4.184$

tp = days after conception

MTE_t, Mcal/d = maintenance energy at d t

MIE_t, Mcal/d = milk energy at d t

Changes in BW result from energy deficits or surpluses. When the IE is lower than the required energy (RE), weight loss occurs. The opposite occurs when the IE is greater than the RE. Body weight was used to estimate changes in body reserves.

Table 3-5. Algebraic equation representing IE in the proposed model.

$IE_t = b_1 [(TBW-BW_{(t-1)}/TBW] + b_2 MTE_{(t-1)} + b_3 MIE_{(t-1)} + b_4 PGE_{(t-1)}$

Definition

IE_t, Mcal/d = intake energy at d t
b_1, Mcal/kg = parameter (partial regression coefficient)[a]
TBW, kg = target BW; BW just prior to calving
$BW_{(t-1)}$, kg = body weight at d t-1
b_2 = parameter (partial regression coefficient)[a]
$\alpha_2 x b_2$, Mcal/d = estimate of energy requirement for maintenance[a]
$MTE_{(t-1)}$, Mcal/d = maintenance energy ($\alpha_2 xBW^{.75}$) at d t-1
b_3 = parameter (partial regression coefficient)[a]
$\alpha_3 x b_3$, Mcal/d = estimate of energy requirement for milk production[a]
$MIE_{(t-1)}$, Mcal/d = milk energy (α_3xFCM) at d t-1
b_4 = parameter (partial regression coefficient)[a]
$PGE_{(t-1)}$, Mcal/d = pregnancy energy at d t-1

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[a] As estimated with data set using FMINS.

The model was constructed so that IE was driven by energy requirements for maintenance, pregnancy and milk production as well as those requirements to attain a TBW (Table 3-5). The TBW was defined as the BW of the cow just before parturition because this theoretically represents the maximum BW for any lactational cycle of a mature cow and includes BW associated with pregnancy. A healthy, nutritionally well-managed cow should be able to deposit the weight equivalent to body reserves mobilized during early lactation in late lactation or by the end of the dry period, reaching parturition with the same BW she had just prior to calving of the previous lactation cycle.

Table 3-6. Algebraic equation representing 4% FCM in the proposed model.

If $AE_{mp}/RE_{mp} \geq 1$

$$FCM_t = [A\, t^b\, e^{-ct}]_{FCM}$$

If $AE_{mp}/RE_{mp} < 1$

$$FCM_t = [A\, t^b\, e^{-ct}]_{FCM}\, AE_{mp}/RE_{mp}$$

Definition

AE_{mp}, Mcal/d	=	available energy for milk production
	=	$IE_{(t-1)} - MTE_{(t-1)} - PGE_{(t-1)} - BER$
RE_{mp}, Mcal/d	=	required energy for milk production
	=	$\alpha_3\, [A\, t^b\, e^{-ct}]_{FCM}$
α_3, Mcal/kg	=	energy requirement for 4% FCM production (NRC, 1989)
FCM, kg/d	=	4% FCM
$[A\, t^b\, e^{-ct}]_{FCM}$, kg/d	=	milk potential corrected for FCM (Wood, 1967)
$IE_{(t-1)}$, Mcal/d	=	intake energy at d t-1
$MTE_{(t-1)}$, Mcal/d	=	maintenance energy at d t-1
$PGE_{(t-1)}$, Mcal/d	=	pregnancy energy at d t-1
BER, Mcal/d	=	body energy reserves
	=	$\alpha_4\, [BW(t) - BW(t-1)]$
α_4, Mcal/kg	=	energy requirement for BW change (NRC, 1989)

The parameters of the IE equation (b_1, b_2, b_3 and b_4) are partial regression coefficients (Table 3-5). The product of the estimated parameter (b_i) and its corresponding energy requirement (α_i) is the estimate of the energy requirement obtained with the data set using the optimization technique FMINS. The parameter b_1 represents an estimate of the energy requirement to produce a change in BW difference (TBW - BW) as estimated by FMINS technique.

It was assumed that if the energy available for milk production was greater than or equal to the energy required, the cow produced milk to a potential represented by Wood's equation (Wood, 1967), and partitioned any excess energy to BW gain. However, if the energy available for milk production was less than required, the potential milk production was reduced according to the availability of energy (Table 3-6).

The definition of energy available (EA) for milk production was based on the priorities of energy use during lactation. Maintenance energy was regarded as first priority and therefore, considered a fixed requirement to be deducted from IE. Likewise, PGE was considered also a fixed requirement to be deducted from IE after conception. The MIE had priority in the use of any excess energy over BER at any stage of lactation.

The parameters of Wood's equation (Wood, 1967) were estimated using PROC NLIN procedure which fits nonlinear regression models by least squares (SAS, 1985).

Day of conception, a modifiable input of the model, was set on d 129 of lactation. At least a portion of the cows used in the Monsanto trial were pregnant by d 129. Conception dates were not available. Therefore, an acceptable value for days open for the state of Florida (129 d) was used as the average day when cows conceived in this data set (Harris and Webb, 1993). Because no information on conception date was available for the NH data set, and because at least some cows in this data set likely were pregnant, the same value (129 d) was used. For the Kodak data set, the mean value (119 d) of the reported days open was used.

Analytical Procedure

Because of differences in actual DMI, 4% FCM and BW over the course of lactation among data sets (Figures 3-1, 3-2 and 3-3), model parameters for each data set were estimated. The optimization technique and the simultaneous solution of the equations were implemented with Matlab (1993). An implementation of the Nelder-Meade (1965) simplex algorithm (FMINS, in the Matlab toolbox) was used to estimate the parameters in the IE equation. It is a direct search technique for finding the minimum of a function with several independent variables. This multivariable function (F) was defined as the summation of the residual sums of squares of the actual values and those predicted by the model corresponding to DMI, FCM and BW (Table 3.7). The mean square error of the model (MSE_m) defined as the ratio of this function and the number of observations minus the number of estimated parameters, describes how accurate the model is at predicting the experimental data (Table 3-7).

The mean square prediction error ($MSPE_e$) and mean prediction error (MPE_e) were calculated for each independent equation of the model to identify and quantify the lack of accuracy in predicting each component of the model. The $MSPE_e$ is defined as the summation of the residual sum of squares of the actual values and those predicted by the model, divided by the number of observations, whereas MPE_e is the square root of $MSPE_e$ (Table 3-7).

The ordinary differential equation was solved by the function ODE 23 in Matlab. The ODE 23 function is an automatic step size Runge-Kutta-Fehlberg integration

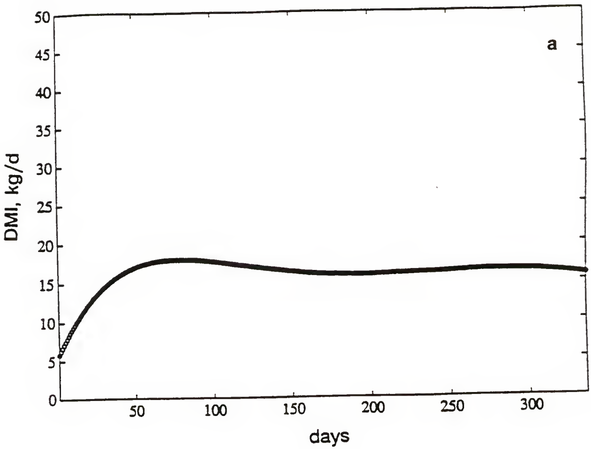

Figure 3-1. Plot of actual DMI (kg/d) during lactation (days): a) for the Monsanto data set, b) for the medium NH data set; c) for the Kodak data set.

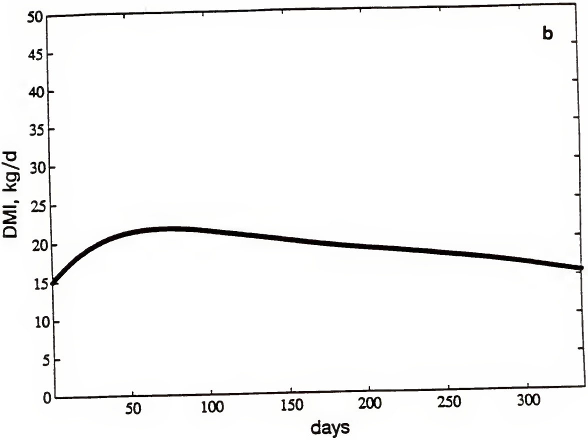

Figure 3-1 (continued).

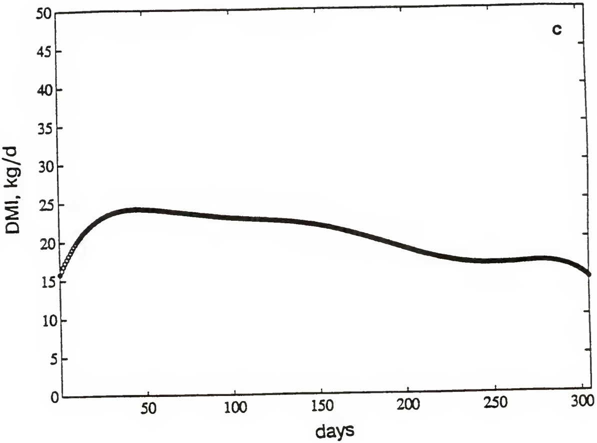

Figure 3-1 (continued).

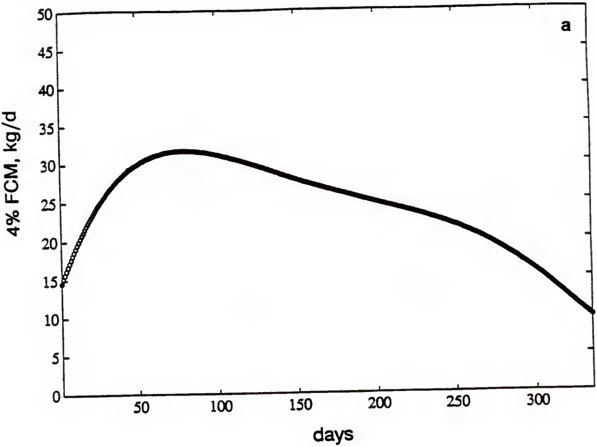

Figure 3-2. Plot of actual 4% FCM (kg/d) during lactation (days): a) for the Monsanto data set, b) for the medium NH data set; c) for the Kodak data set.

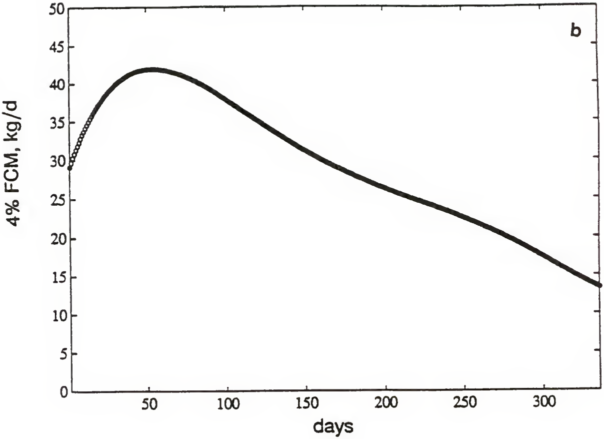

Figure 3-2 (continued).

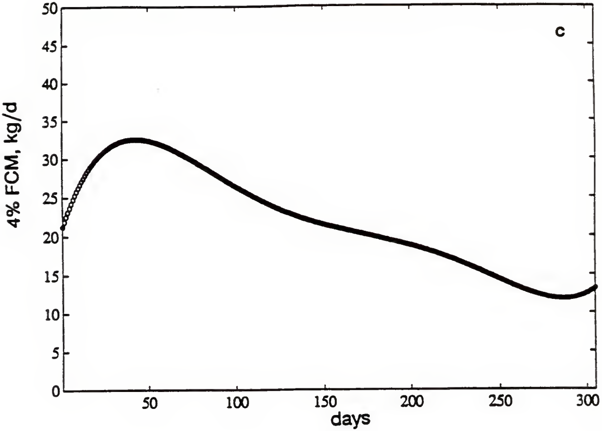

Figure 3-2 (continued).

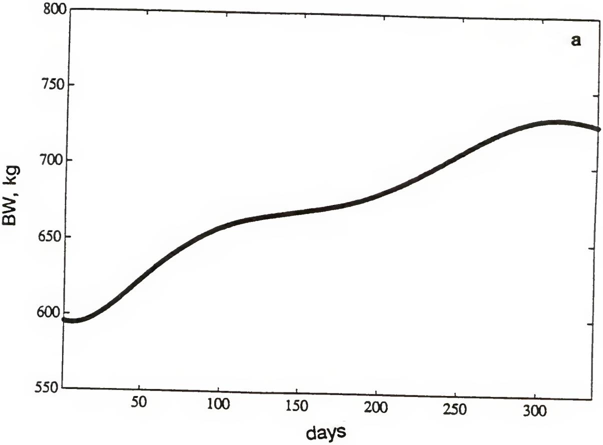

Figure 3-3. Plot of actual BW (kg) during lactation (days): a) for the Monsanto data set, b) for the medium NH data set; c) for the Kodak data set.

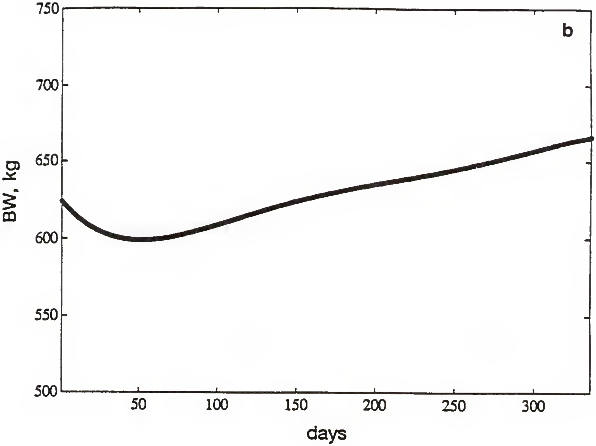

Figure 3-3 (continued).

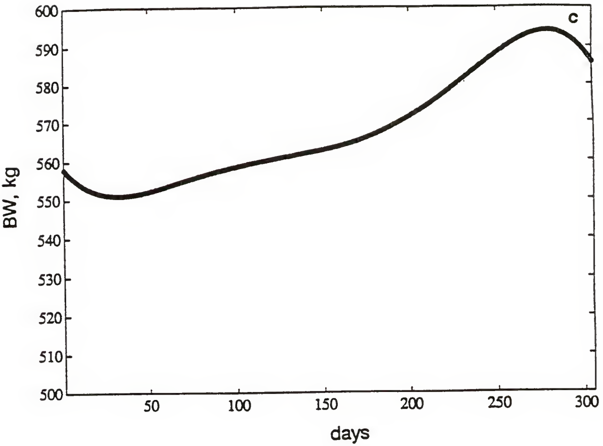

Figure 3-3 (continued).

Table 3-7 Multivariable function to minimize (F), mean square error of the model (MSE_m) and mean square prediction error of each equation ($MSPE_e$).

$$F = \Sigma(ABW - PBW)^2 + \Sigma(ADMI - PDMI)^2 + \Sigma(AFCM - PFCM)^2$$

$$MSE_m = (n - 4)^{-1} F$$

$$MSPE_e = n^{-1} \Sigma (A - P)^2$$

Definition

F, kg^2 = summation of residual sum of squares of actual and predicted values
ABW, kg = actual body weight
PBW, kg = predicted body weight
ADMI, kg = actual dry matter intake,
PDMI, kg = predicted dry matter intake
AFCM, kg = actual 4% FCM production
PFCM, kg = predicted 4% FCM production
A, kg = actual value
P, kg = predicted value
n = number of observations
MSE_m = mean square error of the model
$MSPE_e$ = mean square prediction error of each equation

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method (Forsythe et al., 1977). The three equations comprising the model were solved simultaneously. The experimental responses (referred to as actual responses) for DMI, 4% FCM and BW were compared graphically with the predicted responses for each data set.

Results and Discussion

Estimated values of the model parameters for each data set are presented in Table 3-8. The corresponding values of F, $MSPE_m$, $MSPE_e$ and MPE_e are presented in Table 3-9.

The IE was driven by the energy requirements for maintenance, milk production and pregnancy, as well as by the ((TBW-BW)/TBW) ratio. The estimates of energy requirements (α_i) applied to the IE equation, were obtained from calorimetric chamber experiments (Moe et al.,1972; Moe et al., 1971). Experimentation in controlled environmental conditions is the best technique to estimate true parameters. However, parameters estimated under these conditions may not be applicable always under field conditions. As pointed out by Fox et al. (1988), requirements determined under controlled conditions must be adjusted to fit the multitude of animal, management and environmental effects.

Walter and Mao (1989) developed and tested a variety of multiple regression models for net energy intake (NEI) from data collected from cows kept under normal conditions rather than in indirect calorimetric chambers. These authors reported that the mean estimates of the coefficient corresponding to energy requirement for maintenance (.147 to .185 Mcal/kg $BW^{.75}$) were far above those obtained under controlled conditions and those corresponding to milk (.271 to .374 Mcal/kg), were low compared with previously reported values. Ngwerume and Mao (1992) developed a NEI model with data collected from 247 lactating Holstein cows. The energy requirement for production (.54 Mcal/kg) also was below the

Table 3-8. Estimated set of parameters corresponding to the model's IE equation for the Monsanto, Medium NH and Kodak data sets.

Parameter	Monsanto	Medium NH	Kodak
b1, Mcal/d	85.021	116.574	94.41350
b2	2.5218	2.0518	2.15318
b3	.11273	.0541	.45844
b4	-2.1205	.9265	-7.70110

Table 3-9. Minimum residual value (F) and mean square error of the model ($MSE_{m)}$, mean square prediction error ($MSPE_e$) and mean prediction error (MPE_e) of each independent equation of the model.

Evaluator	Monsanto	Medium NH	Kodak
F, kg^2	44609.9	72159.0	22308.0
MSE_m, kg^2	134.37	217.34	74.09
$MSPE_{DMI}$, kg^2/d	12.73	.20	.68
MPE_{DMI}, kg/d	3.57	.45	.83
$MSPE_{FCM}$, kg^2/d	1.01	.98	1.28
MPE_{FCM}, kg/d	1.00	.99	1.13
$MSPE_{BW}$, kg^2	300.29	194.31	64.83
MPE_{BW}, kg	17.83	13.94	8.05

value estimated from cows in energy chambers. The energy requirement for maintenance was estimated to be .15 Mcal/kg of $BW^{.75}$, a higher value than the estimate of the NRC (1989) of .08 Mcal/$kg^{.75}$. The values reported by these researchers are similar in magnitude to the estimate of energy requirements for maintenance (α_2 times b_2) and milk production (α_3 times b_3) obtained for the Monsanto, NH and Kodak data sets using the FMINS technique.

The optimization technique (FMINS) used in the current study solved the three equations simultaneously searching for the minimum sum of squares of the actual values and those predicted by the model corresponding to DMI, FCM and BW. The parameter estimates obtained with this technique are therefore interdependent (lumped parameters) and only represent the best solution of this numerical technique. In order to obtain parameters with biological significance, adequate experimentation should be conducted. The negative signs of the regression coefficient for pregnancy (b_4) obtained with the Monsanto and Kodak data set are also the result of the optimization technique and can not be interpreted biologically. The fact that an average day of conception was set arbitrarily without knowledge of the exact time of conception nor of the number of cows in each data set that conceived may contribute, at least partially, to the value and sign of the estimated parameter (Table 3-8).

Figures 3-4, 3-5 and 3-6 are graphic representations of the actual and predicted responses for DMI, FCM and BW, respectively using the Monsanto data set. DMI was over-predicted in early and mid-lactation (maximum difference was 15.9 kg/d) and under-predicted in late lactation (maximum difference was 3.06 kg/d). The over-prediction being more pronounced during early lactation. Roseler (1994) when testing the accuracy of six intake prediction equations reported that the NRC (1989) equation over-predicted intake in early lactation. The linear coefficients of the NRC (1989) equation being the cause of the large over-prediction observed during wk 2 to 10 of lactation.

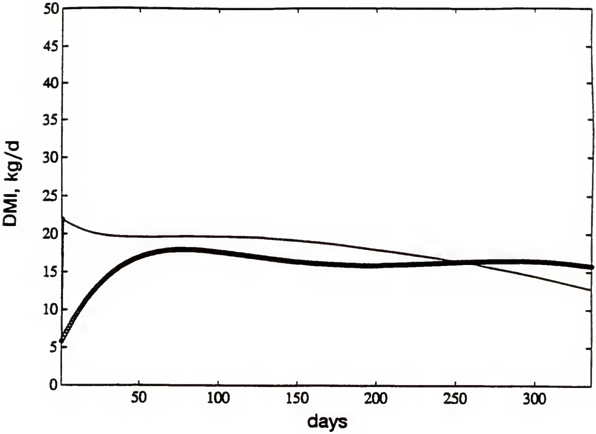

Figure 3-4. Plots of actual (thick line) and model-predicted (thin line) daily DMI (kg/d) using the Monsanto data set.

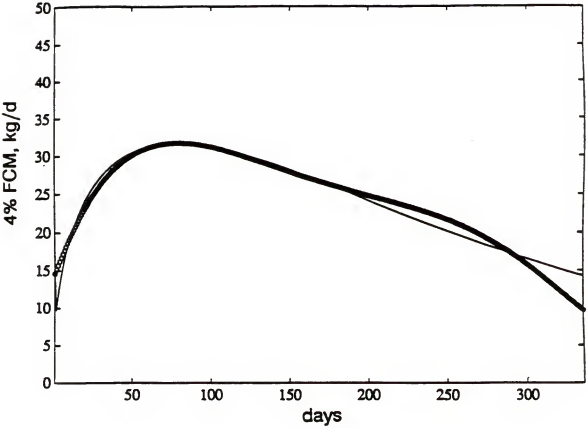

Figure 3-5. Plots of actual (thick line) and model-fitted (thin line) daily 4% FCM (kg/d) using the Monsanto data set.

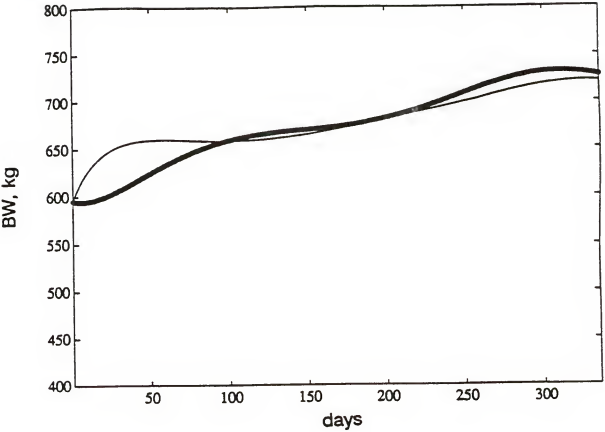

Figure 3-6. Plots of actual (thick line) and model-predicted (thin line) daily BW (kg) using the Monsanto data set.

The model calculated that AE_{mp} was greater than the RE_{mp} throughout lactation and therefore, milk production equaled the potential which was represented by Wood's equation (Wood, 1967). The parameters of this equation were estimated for the data set using PROC NLIN procedure (SAS, 1985). This explains the high degree of similarity between the response curves (Figure 3-5).

The BW figure (Figure 3-6) shows some dissimilarity between actual and predicted responses early in lactation (maximum difference was 45.88 kg). This over-prediction corresponds with the over-prediction of DMI during the same period. Furthermore, the slight under-prediction of DMI in late lactation translated into a slight under-prediction of BW during this same stage of lactation (maximum difference was 8.3 kg).

The plots in Figures 3-7, 3-8 and 3-9 represent the DMI, FCM, and BW of the actual and the predicted responses for the medium NH set. Predicted and actual DMI responses over the lactation period were similar, except for slight deviations in very early lactation (maximum difference was 5.95 kg/d). The FCM yield represented the potential and therefore, fitted the data well. The curve of predicted BW was shifted in time with respect to the actual curve, with the nadir shifted from about 50 d to about 84 d into lactation. However, the model's prediction of mean BW was very close ($\pm$ 2.2 kg) to the actual BW (628.6 kg).

Actual and predicted DMI, FCM, and BW responses for the Kodak data set are plotted in Figures 3-10, 3-11 and 3-12, respectively. The DMI was slightly over-predicted in early lactation (maximum difference was 2 kg/d), the overall prediction response being quite similar to the actual response as depicted by the low MPE_e value (Table 3-9). Based on EA_{mp}, production of milk was represented by Wood's

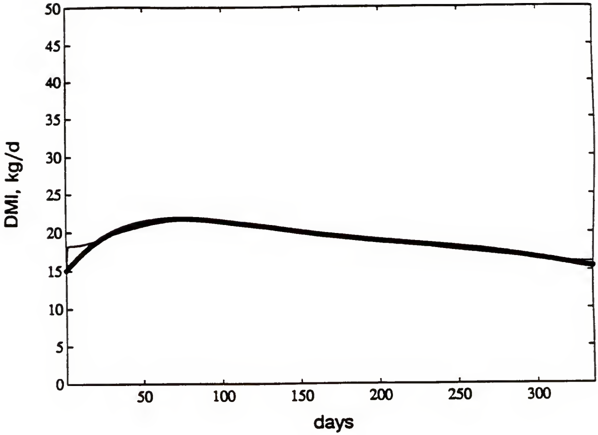

Figure 3-7. Plots of actual (thick line) and model-predicted (thin line) daily DMI (kg/d) using the medium NH data set.

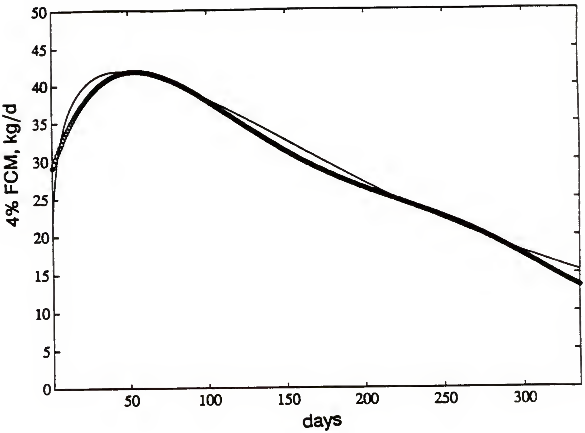

Figure 3-8. Plots of actual (thick line) and model-fitted (thin line) daily 4% FCM (kg/d) using the medium NH data set.

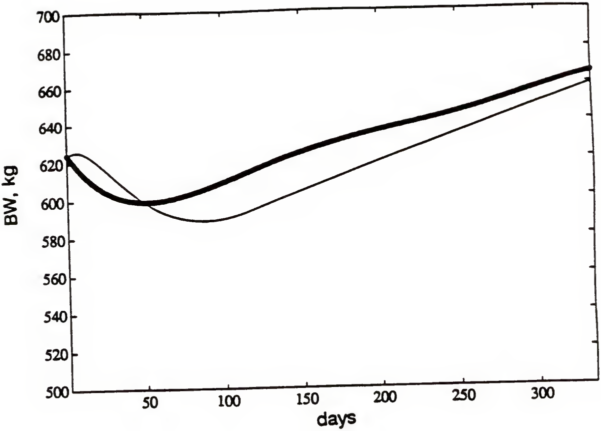

Figure 3-9. Plots of actual (thick line) and model-predicted (thin line) daily BW (kg) using the medium NH data set.

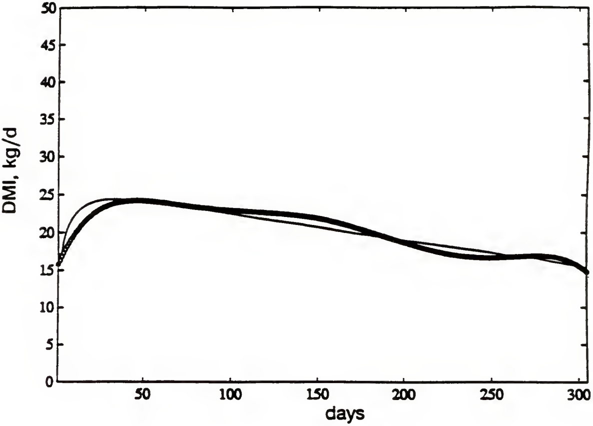

Figure 3-10. Plots of actual (thick line) and model-predicted (thin line) daily DMI (kg/d) using the Kodak data set.

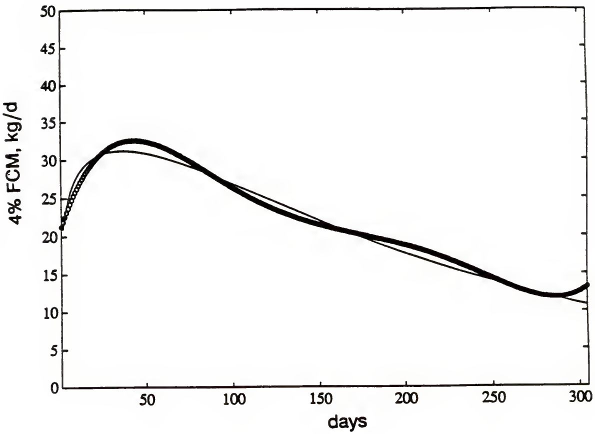

Figure 3-11. Plots of actual (thick line) and model-fitted (thin line) daily 4% FCM (kg/d) using the Kodak data set.

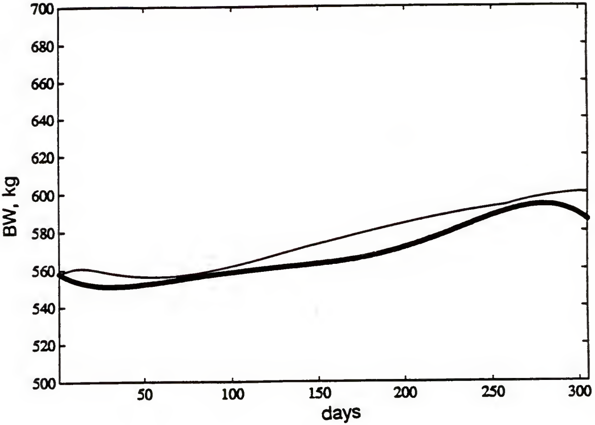

Figure 3-12. Plots of actual (thick line) and model-predicted (thin line) daily BW (kg) using the Kodak data set.

equation (Wood, 1967) and the parameters of this equation were estimated for the data set. This explains the similarity between the response curves. The model slightly over-predicted BW throughout lactation (maximum difference was 12 kg). The over-prediction observed in early lactation being caused by the over-prediction of DMI during the same time interval. The low values of the F function, MPE_m as well as the $MSPE_e$ and MPE_e indicate that the model predicted quite well the actual DMI, FCM and BW responses for this data set.

The actual responses of the Monsanto data were predicted poorly compared with those of the other two data sets. The technique used to characterize DMI, 4% FCM and BW was not a source of error. Figure 3-13 to 3-15, are graphic representations of the unadjusted weekly mean values of DMI, 4% FCM and BW values of the Monsanto data. The adjusted values were within the same ranges as the unadjusted values. The poor prediction of the actual data may be due to the set of estimated parameters. The values of these parameters may not be the optimum values for this data set. Probably there is a set of parameters that results in a lower F value and therefore, a better prediction of the actual data. The optimization procedure is a search technique to find a function's minimum, based on initial values (or starting guesses) of the parameters to be estimated. In this case, it is probable that the initial guesses used resulted in a less than optimal set of parameters.

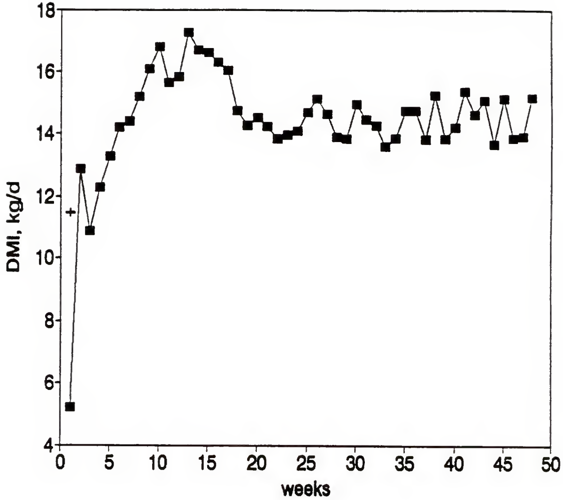

Figure 3-13. Plot of unadjusted mean values of DMI (kg/d) during lactation (weeks) for the Monsanto data set.

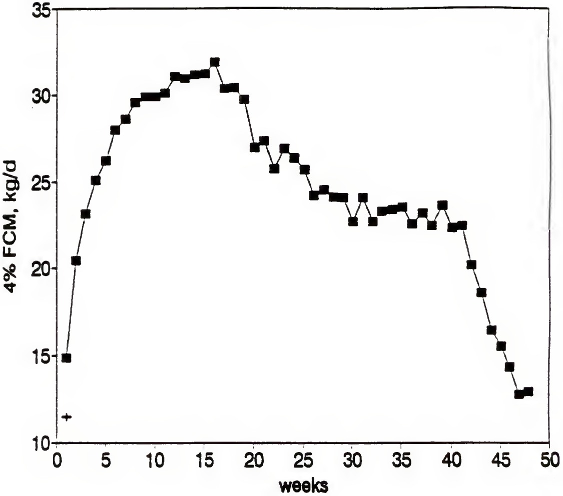

Figure 3-14. Plot of unadjusted mean values of 4% FCM (kg/d) during lactation (weeks) for the Monsanto data set.

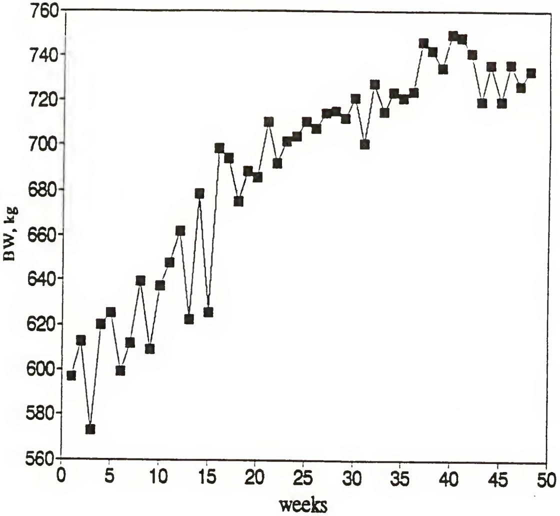

Figure 3-15. Plot of unadjusted mean values of BW (kg/d) during lactation (weeks) for the Monsanto data set.

Overall, the model's predictive ability was reasonably acceptable when tested with each of the three data sets as shown by the values of MSE_m and MPE_e and by the graphic representations of the actual and predicted responses for DMI, FCM and BW.

Summary and Conclusions

In this chapter, a dynamic model that quantitatively represents the energy transactions of the multiparous cow was developed. Intake energy was driven by MTE, PGE, and MIE requirements and the energy requirement to attain a TBW. The FCM equation was based on the concept of milk production potential and the influence of the diet, BER and energy requirements on milk potential. A differential equation was used to calculate BW, assuming that changes in BW resulted from changes in energy deficits or surpluses.

Model parameters were estimated for each data set. Based on the actual DMI, MY and BW responses and the parameter values of each data set, it was concluded that the data sets were substantially different from each other, particularly the Monsanto data set. The energy requirements estimated using the optimization technique differed substantially from the estimates obtained under controlled experimentation (Moe et al., 1972; Moe et al., 1971). In the current study, these estimates represent the combination of parameter estimates (b_1, b_2, b_3, b_4) yielding the best fit by the optimization technique. Biological meaning could not be assigned to these estimates.

Based on the $MSPE_m$ and MPE_e values and the graphs of predicted vs. actual responses for DMI, FCM and BW, the model's prediction performance was considered satisfactory.

CHAPTER IV
QUALITATIVE EVALUATION OF THE MODEL

Introduction

The large demand for energy by high producing cows and the high cost of feeds require the dairy farmer to have accurate knowledge of how a change in the energy concentration of the diet can affect IE, BER and milk production over time. In some situations it might be economically feasible to feed a diet with lower energy density even if yield is below the potential of the cows. In this case, farmers also should be able to predict the extent to which energy concentrations of the diet can be lowered without affecting milk production. In other words, they need to know the extent to which the cow can compensate for the lower energy density of the diet by increasing DMI and (or) mobilizing BER. Or if the energy concentration of the diet is too low, farmers should be able to predict the degree by which milk production will be affected.

Evaluation of a model is concerned with aspects such as appropriateness (to objectives), goodness of fit, simplicity and utility. It is usual to first examine the qualitative behavior of the model, and if this is satisfactory and if appropriate data are available to proceed to a quantitative fitting (France and Thornley, 1984). Sorensen (1990) defined validation (France and Thornley used the term evaluation instead of validation) as the evaluation of the behavior of the model in relation to the behavior of the real system. Sorensen (1990) distinguished between two types of validation techniques: goodness of fit test and other techniques such as face validity, trace validity and sensitivity analysis.

Goodness of fit is based on the degree of conformity of predicted and observed responses. Face validity is performed by asking people with knowledge of the system, to determine if the model is reasonable by means of flow charts. Trace validity is done by following entities in the model to determine if the logic is correct (Sargent, 1982). There are two distinguishable types of sensitivity analysis. One kind of sensitivity analysis is to manipulate decision variables in order to determine the range of acceptable results. The other kind is to evaluate the effects of changes in fixed parameters of the model (Sorensen, 1990).

The model developed in the current research was constructed to be the first step towards a management decision-making tool. Accurate economic decisions are dependent on accurate predictions of performance through time. The purpose of this study was to evaluate in a qualitative manner the model's capacity to predict production responses (DMI, MY, BW) to proposed changes in dietary energy concentrations. This evaluation would fit Sorensen's (1990) definition of sensitivity analysis where decision variables are manipulated in order to evaluate the range of acceptable results.

Materials and Methods

Experimental Data Sets

The Monsanto, the medium NH and the Kodak data sets described in the previous chapter, were used to evaluate the model qualitatively.

Mathematical Model

Slight modifications were performed to the model described in the previous chapter. The first modification consisted in setting a limit on daily DMI. There is a practical limit to the amount of DMI cows can consume daily (NRC, 1989; Mertens, 1987; Harris, 1990). In this model, this limit, expressed as a percentage of the BW, was imposed independently each day as the BW of the cow changed through time. Dry matter intake can be estimated by dividing IE by the dietary NEL concentration. Intake energy was assumed to be driven by the MTE, PGE and MIE requirements of the cows. Therefore, the maximum DMI capacity was calculated by dividing the summation of energy requirements (NRC, 1989) by the dietary NEL concentration. For the Monsanto and Kodak data sets the maximum calculated DMI was 4.0% of BW, whereas for the NH data set the calculated value was 4.5% of BW. This difference was the result of differences in energy requirements and NEL concentrations among data sets.

The second modification consisted of setting a limit to the maximum amount of BW loss possible from the first day of lactation to its nadir. Studies conducted at the Cornell University (Ferguson, 1988; Smith et al, 1983) demonstrated that cows losing more than 1 BCS during lactation had reduced fertility. From a table of available BER at various BW and BCS (Fox, 1991) it was estimated that for a 545 kg cow a change of 1 BCS from 3.5 to 2.5 generates or requires 400 Mcal, that is .0025 BCS/Mcal. On average, a change of 1 kg of BW generates or requires 6 Mcal of body tissue energy (Moe and Tyrrell, 1974), that is .2 kg/Mcal. From these relationships it was inferred that .2 kg/.0025 BCS = 80 kg/BCS change. The maximum reduction in BW imposed was thus set at 80 kg from the BW of the cows at the start of lactation. Because this model was intended as a practical management tool, this seemed an appropriate limit.

Evaluation Procedure

In the original data sets, dietary NEL concentrations between d 1 to 112, 113 to 224, and 225 through the end of lactation were as follows: 1.7, 1.7 and 1.54 Mcal/kg of DM for the Monsanto data set; 1.69, 1.55 and 1.52 Mcal/kg of DM for the medium NH data set; and, 1.709, 1.685 and 1.665 Mcal/kg of DM for the Kodak data set. To evaluate the model, NEL concentration across the entire lactation was set at 1.5, 1.35, 1.25 and 1.1 Mcal/kg of DM, each in separate runs of the model. The DMI, FCM and BW responses to changes in the dietary energy concentration were represented graphically and will be referred to as predicted responses. These response curves were compared with the actual response curves generated with the original dietary NEL concentrations of each data set.

Results and Discussion

Monsanto Data Set

When the energy concentration of the diet was reduced from the original values to 1.5 Mcal/kg of DM throughout lactation, the model predicted an increase in DMI and no changes in either BW or FCM production compared with the predicted response curves generated by the model in Chapter III (Figures 4-1 to 4-3 compared with Figures 3-4 to 3-6). Moreover, DMI never reached the imposed limit. This would indicate that the NEL concentration was not limiting intake, and that the model predicted an increased intake of a diet with a lower NEL density to maintain the same MY and BW.

Predicted responses with the model were consistent with known biological interrelationships among DMI, FCM and BW of cattle. As described by Baile and Forbes (1974) ruminants try to compensate for changes in the energy inputs by altering their voluntary feed intake over time. Montgomery and Baumgardt (1965) demonstrated experimentally that cows fed diets with lower energy concentration (2.55 Mcal of DE/kg of DM) had higher DMI ($P < .05$) than those cows fed diets with higher energy concentrations (3.15 Mcal of DE/kg of DM).

When the NEL concentration of the diet was lowered to 1.35 Mcal/kg of DM the model predicted a further increase of the DMI compared with the original prediction (Figure 3-4), reaching the imposed maximum (4% of BW) at times when the production demand was highest. The model predicted no changes in BW or FCM in response to lower dietary energy concentration (1.35 Mcal/kg of DM; Figures 4-4 to 4-6).

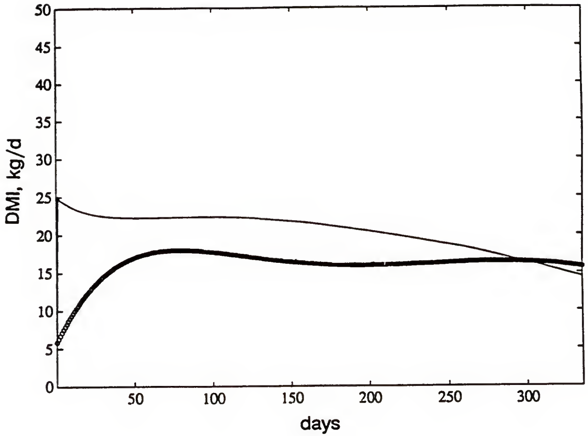

Figure 4-1. Plots of actual daily DMI (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.5 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

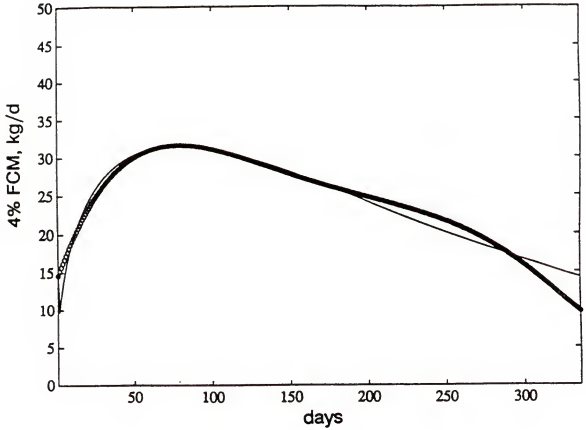

Figure 4-2. Plots of actual 4% FCM (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.5 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

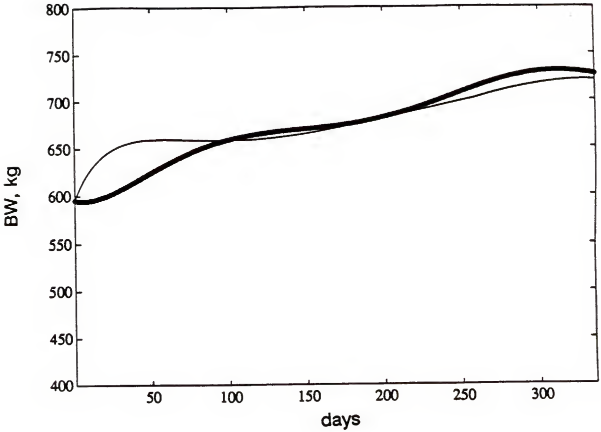

Figure 4-3 Plots of actual BW (kg) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.5 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

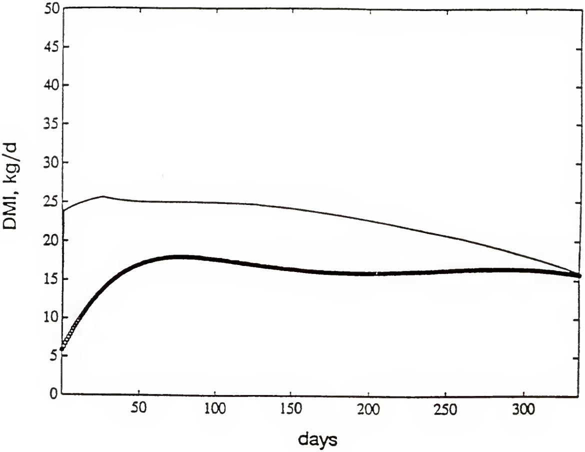

Figure 4-4. Plots of actual daily DMI (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.35 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

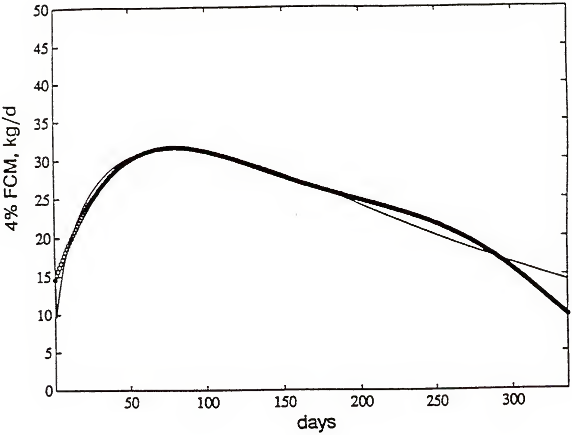

Figure 4-5. Plots of actual daily 4% FCM (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.35 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

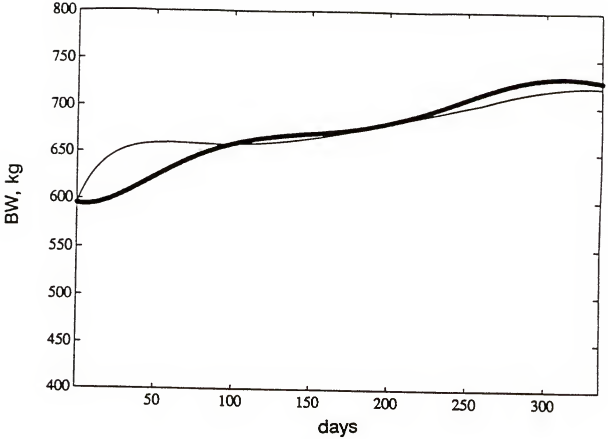

Figure 4-6. Plots actual daily BW (kg) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.35 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

The extent to which the lactating cow fails to meet its energy requirements will affect MY and BW loss (Forbes, 1977b). When the energy concentration of the diet was lowered further (1.25 Mcal/kg of DM), the model predicted an increase in DMI to the maximum capacity (4% of BW) throughout most of the lactation (Figure 4-7) compared with the original prediction by the model (Figure 3-4). However, because the amount of energy supplied by the diet was not enough to support the current amount of milk production (Figure 4-8), the model predicted a loss of BW (Figure 4-9). The model predicted a sharp decrease in DMI after d 250 of lactation. This represented the time when substantially less DMI was necessary to meet the lower energy demand (Figures 4-7 to 4-9).

One common practice to maximize IE of high producing cows is to increase the energy density of the diet by decreasing the proportion of forage and increasing the proportion of concentrate in the diet. Results of several studies (Bailey, 1989; McLeod et al., 1983a, 1983b; Eastridge et al., 1988; Krohn and Andersen, 1980) demonstrated that DMI was highest for cows consuming diets with lowest forage-to-concentrate ratio. This has been explained by the lack of rumen capacity for sufficient consumption of high forage, low energy density diets. In all experiments, cows receiving the low energy diets lost more BW than cows consuming higher energy density diets.

Cows fed low energy density diets must mobilize greater amounts of BE than cows fed diets of higher energy densities (Krohn and Andersen, 1980). In the current study, a further reduction of the NEL concentration of the diet (1.1 Mcal/kg

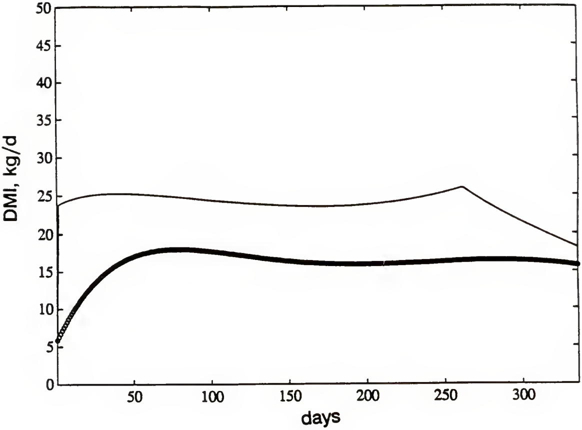

Figure 4-7. Plots of actual daily DMI (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

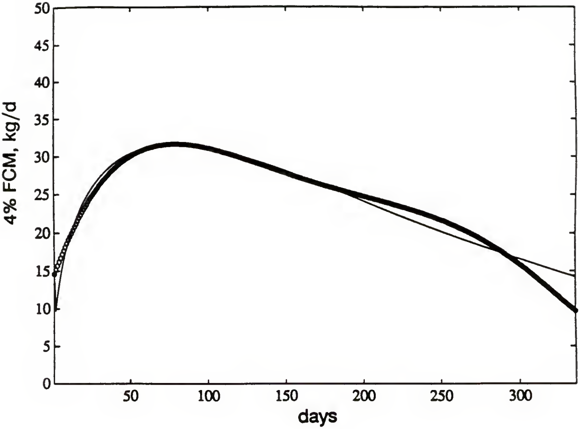

Figure 4-8. Plots of actual daily 4% FCM (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

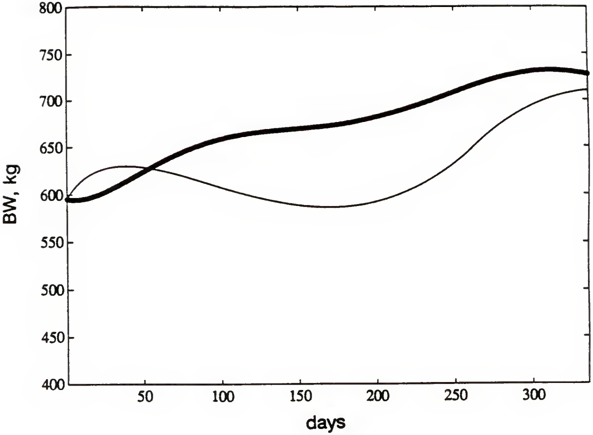

Figure 4-9. Plots of actual daily BW (kg) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.35 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

of DM) resulted in an even greater predicted BW loss response than observed with diets of higher energy density. The model predicted that BW was lost until the imposed limit of BW loss was reached (80 kg from the first day of lactation to nadir). At this point (d 94 of lactation), because the total energy input (feed plus body reserves) was not sufficient to meet the energy requirements for milk production a sudden decrease in FCM yield was predicted. In reality, a more gradual decrease in FCM yield is likely to occur after a reduction in dietary NEL. However, no accurate description of this adaptation mechanism exists currently. Predicted DMI reached the maximum limit (4% of BW) during the first 94 d of lactation. After this point, the model predicted a lower DMI due to the decrease in energy demand for milk production (Figures 4-10 to 4-12).

NH Data Set

A reduction in the dietary NEL concentrations from the original values of 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively, to 1.5 Mcal/kg of DM throughout lactation resulted in an increase in the predicted DMI with no changes in either BW or 4%FCM production compared with the original model prediction (Figures 4-13 to 4-15 vs. Figures 3-7 to 3-9). The DMI curve was driven by the energy demand for maintenance, pregnancy and milk production.

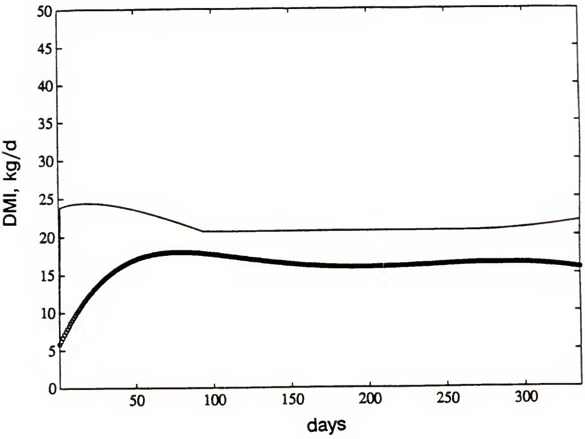

Figure 4-10. Plots of actual daily DMI (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

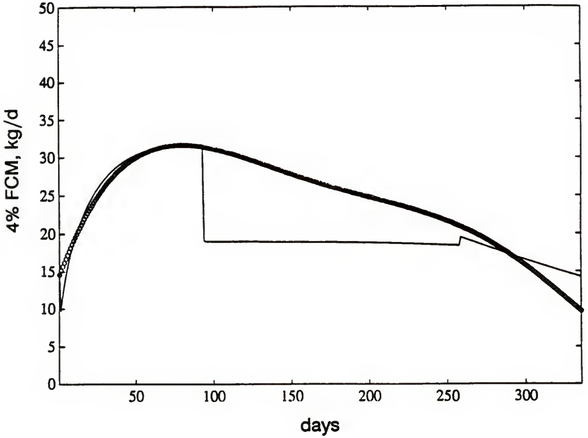

Figure 4-11. Plots of actual daily 4% FCM (kg/d) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

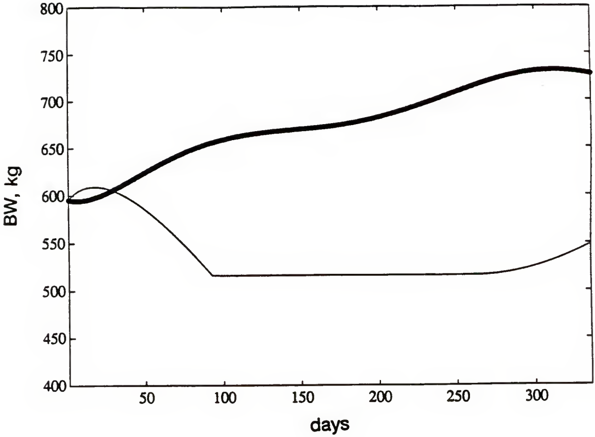

Figure 4-12. Plots of actual daily BW (kg) with 1.7, 1.7 and 1.54 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Monsanto data set.

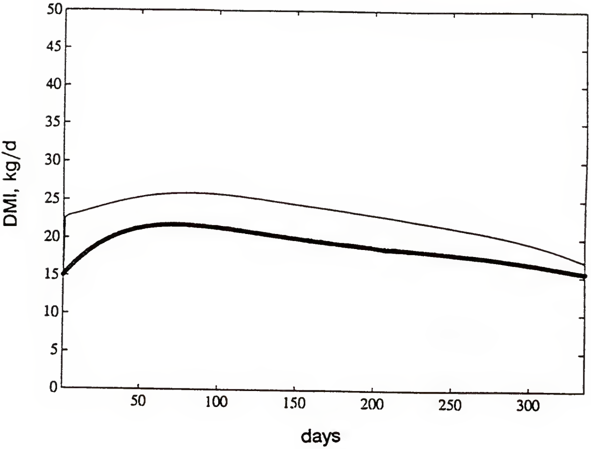

Figure 4-13. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.5 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

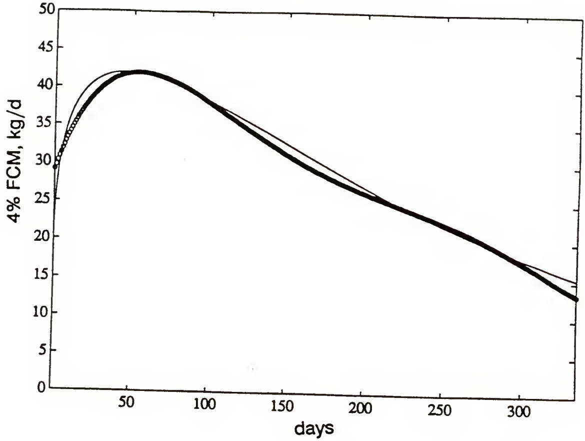

Figure 4-14. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.5 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

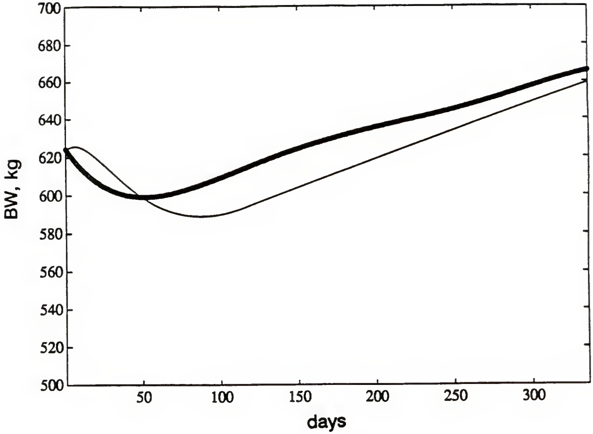

Figure 4-15. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.5 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

When the energy concentration of the diet was lowered to 1.35 Mcal/kg of DM, the model predicted that DMI reached the imposed 4.5% BW limit around day 35 of lactation, and subsequently BW decreased to the maximum imposed limit (80 kg) as energy demand peaked. When the energy available from feed and body reserves was not sufficient to meet the energy demand for milk production, the model predicted a decrease in the rate of FCM production (d 106 of lactation). The flat portion of the predicted FCM curve was the result of the constant DMI (4.5% BW) and no change in BW (Figures 4-16 to 4-18).

The higher energy requirements for milk production in the medium NH data set (mean MY of 29.9 kg/d) compared with that of the Monsanto set (mean MY of 24.18 kg/d), explains why in the medium NH data set (Figure 4-18) the maximum predicted BW loss limit was reached with a higher energy density diet (1.35 Mcal/kg of DM) compared with the Monsanto data set (Figure 4-12; 1.1 Mcal/kg of DM). After the energy demand for milk production had decreased, the model predicted an incremental increase in BW which would correspond to the deposition of body reserves (Figure 4-18).

With a further decrease in the NEL concentration of the diet (1.25 Mcal/kg of DM) the model predicted DMI to be at its maximum (4.5% of BW) throughout lactation and the maximum loss of BW (80 kg) occurring by d 70 of lactation. Because energy from feed and BER was not sufficient to meet energy demands for MY, the model predicted a sudden decrease in milk production. Milk production rate decreased at exactly the same time (d 70 of lactation) as BW reached its nadir. The decrease in FCM was more pronounced than when a

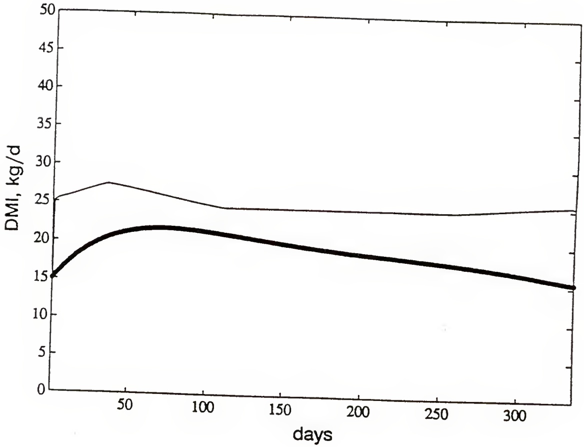

Figure 4-16. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.35 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

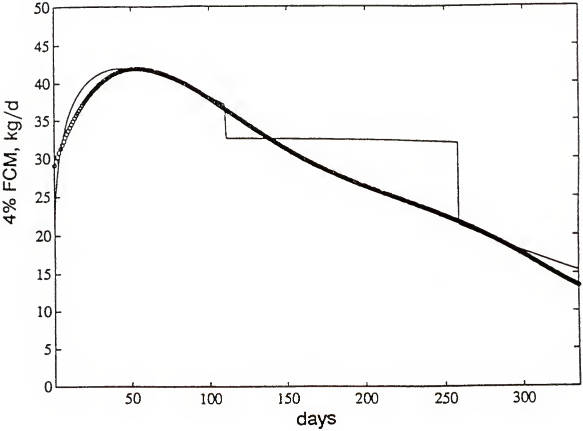

Figure 4-17. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DMI for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily 4% FCM (kg/d) with 1.35 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

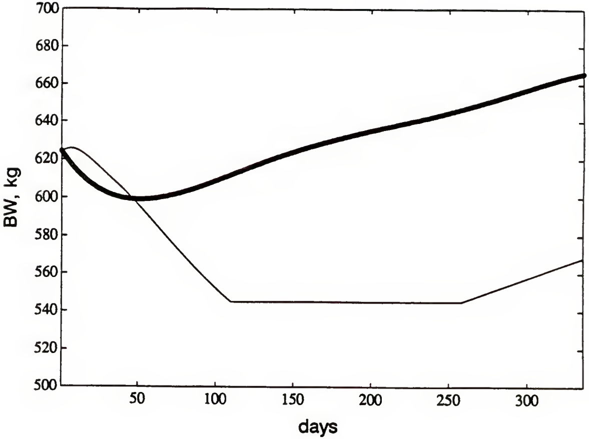

Figure 4-18. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.35 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

higher energy density ration (1.35 Mcal/kg of DM) was used to evaluate the model (Figures 4-19 to 4-21)

Finally, with a dietary NEL concentration of 1.1 Mcal/kg of DM all the above mentioned responses occurred earlier in lactation and as expected the rate of milk production was noticeably lower (Figures 4-22 to 4-24).

Kodak Data Set

When the energy concentration of the diet was reduced from the original values of 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively to 1.5 Mcal/kg of DM throughout lactation, the model predicted an increase in DMI and no changes in either BW or FCM (Figures 4-25 to 4-27) compared with predicted responses generated in Chapter III (Figures 3-10 to 3-12). The model predicted an increase in DMI of a diet with lower NEL density to avoid changes of MY and BW.

When the NEL concentration of the diet was lowered to 1.35 Mcal/kg of DM the model predicted a further increase of the DMI, reaching the imposed maximum (4% of BW) throughout most of lactation compared with the original model prediction with the original NEL concentrations. During peak energy demand, the energy available from the feed was not enough to support the current level of MY, therefore, the model predicted a slight loss of BW (Figures 4-28 to 4-30).

When the energy concentration of the diet was reduced further (1.25 Mcal/kg of DM), the model predicted an increase in DMI to its maximum limit

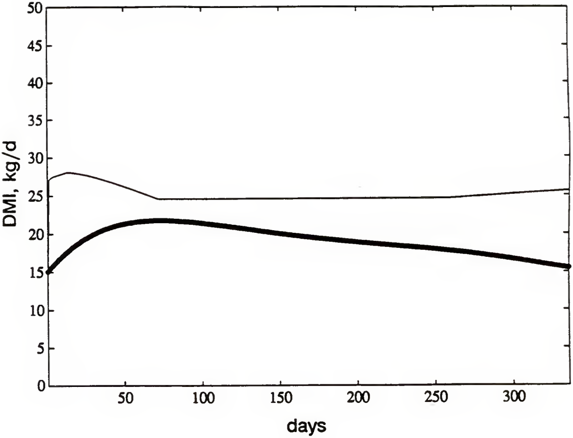

Figure 4-19. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

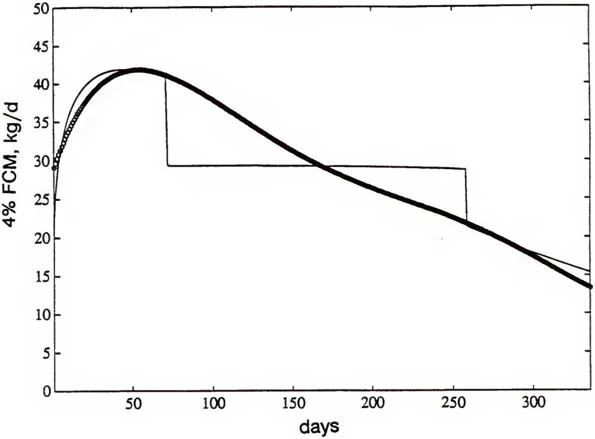

Figure 4-20. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily 4% FCM (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

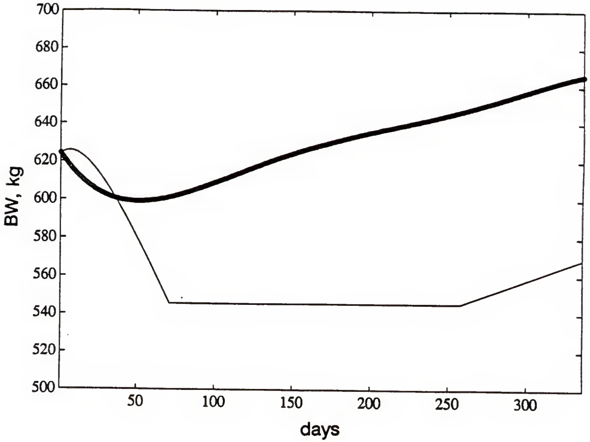

Figure 4-21. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

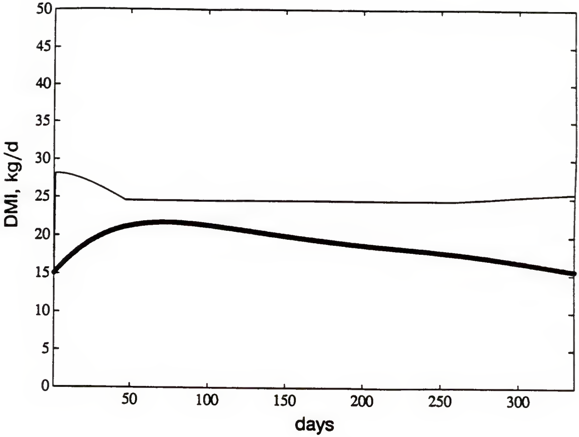

Figure 4-22. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

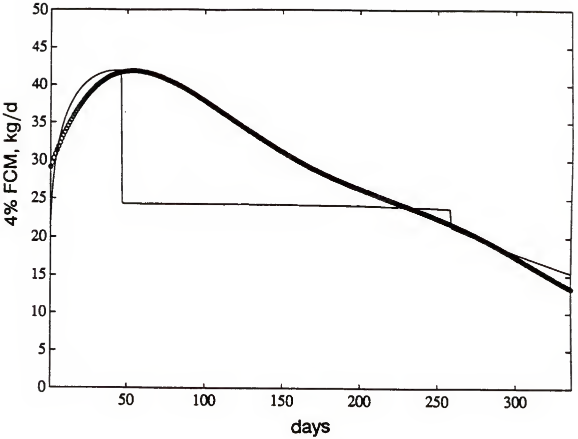

Figure 4-23. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily 4% FCM (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

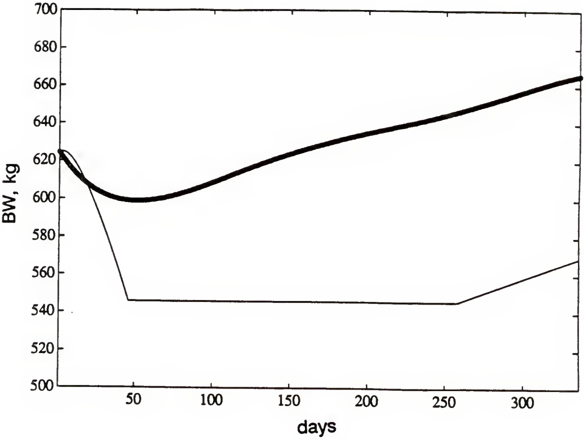

Figure 4-24. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set.

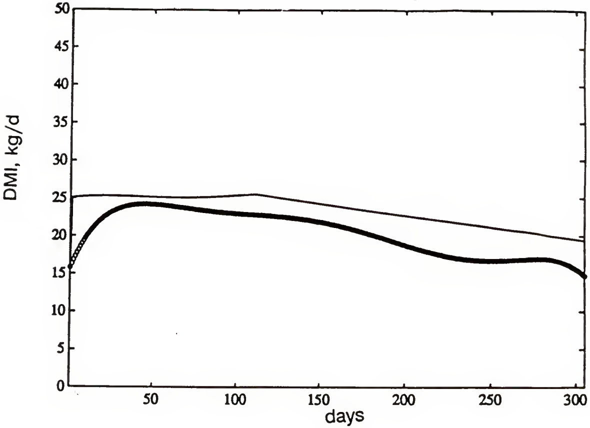

Figure 4-25. Plots of actual daily DMI (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.5 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

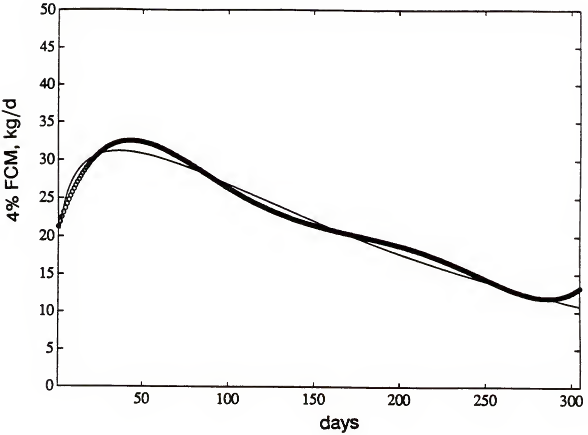

Figure 4-26. Plots of actual daily 4% FCM (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.5 Mcal/kg of DM throughout lactation for the Kodak data set.

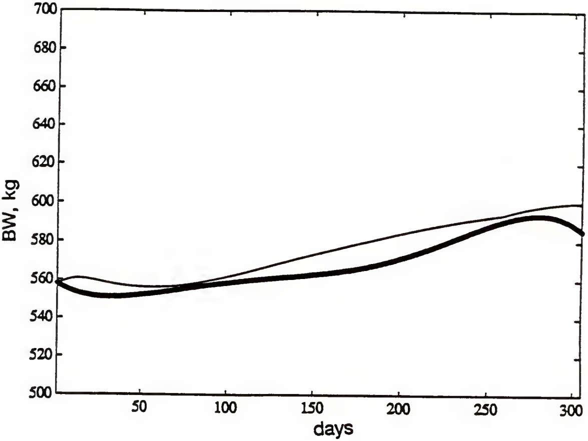

Figure 4-27. Plots of actual daily BW (kg) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily BW (kg) with 1.5 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

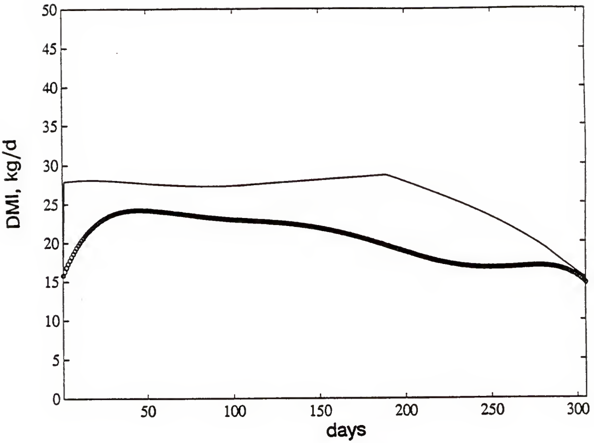

Figure 4-28. Plots of actual daily DMI (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.35 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

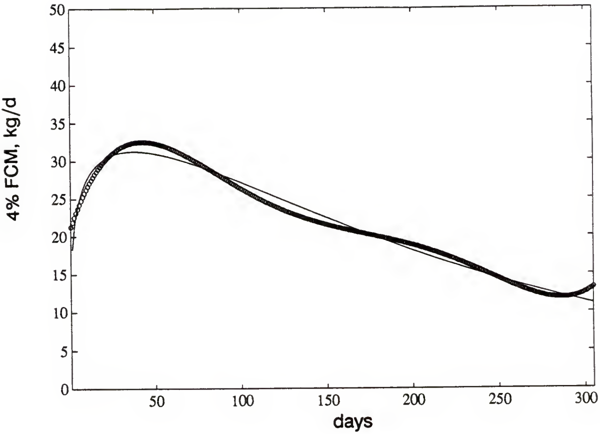

Figure 4-29. Plots of actual daily 4% FCM (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.35 Mcal/kg of DM throughout lactation for the Kodak data set.

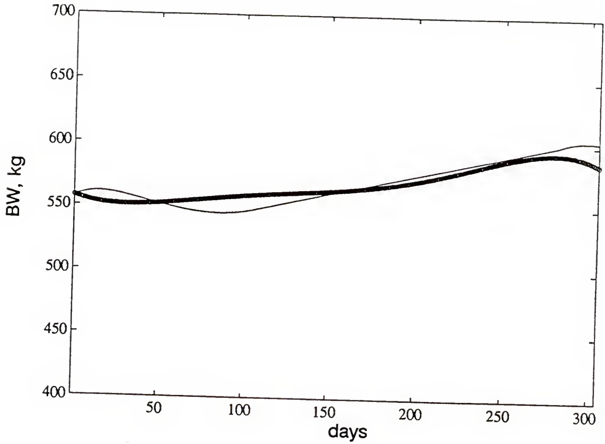

Figure 4-30. Plots of actual daily BW (kg) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily BW (kg) with 1.35 Mcal/kg of DM throughout lactation for the Kodak data set.

(4% of BW) throughout most of the lactation and loss of BW in order to maintain the current level of MY. When the energy demand for milk production was considerably lower, the model predicted less DMI as indicated by the sharp decrease after d 250 of lactation (Figures 4-31 to 4-33).

When the dietary NEL concentration of the diet was reduced to 1.1 Mcal/kg of DM, the model predicted BW loss until the imposed limit of 80 kg was reached. At this point, because the total energy input (feed plus body reserves) was not sufficient to meet the energy requirements for milk production, a sudden decrease in FCM yield was predicted. The model predicted a simultaneous reduction of DMI due to the sharp decrease in energy demand for milk production (Figures 4-34 to 4-36).

Without the maximum DMI limit, the model's response to successive reductions in dietary energy concentrations was an indefinite increase in DMI. Figures 4-37 to 4-39 show that the predicted DMI was unrealistically high (as high as 36 kg of DM), whereas no changes in BW or MY were predicted by the model when NEL concentration of the diet was 1.1 Mcal/kg.

Similarly, when no limit was set for the total amount of BW loss, in order to maintain the same level of milk production, the model allowed unsustainable losses of BW, which in turn resulted in predictions of unrealistic DMI values (Figures 4-40 to 4-42).

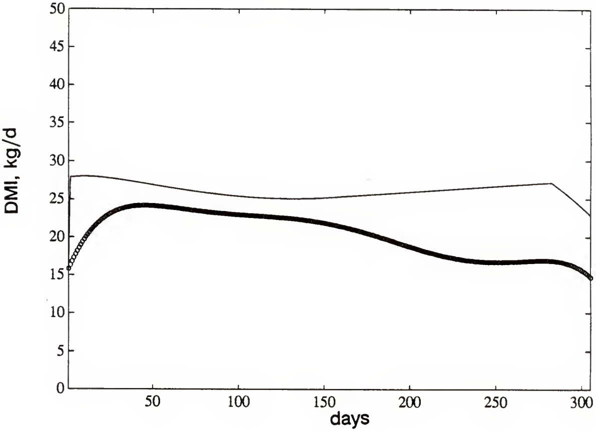

Figure 4-31. Plots of actual daily DMI (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.25 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

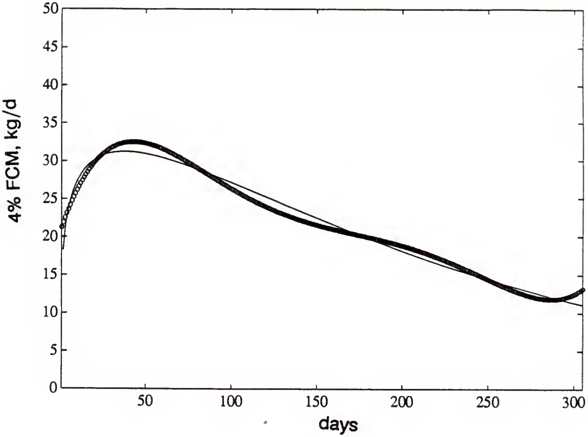

Figure 4-32. Plots of actual daily 4% FCM (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) fitted daily 4% FCM (kg/d) with 1.25 Mcal/kg of DM throughout lactation for the Kodak data set.

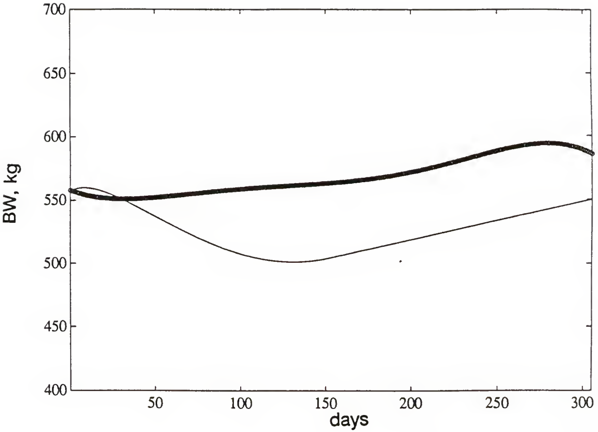

Figure 4-33. Plots of actual daily BW (kg) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily BW (kg) with 1.25 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

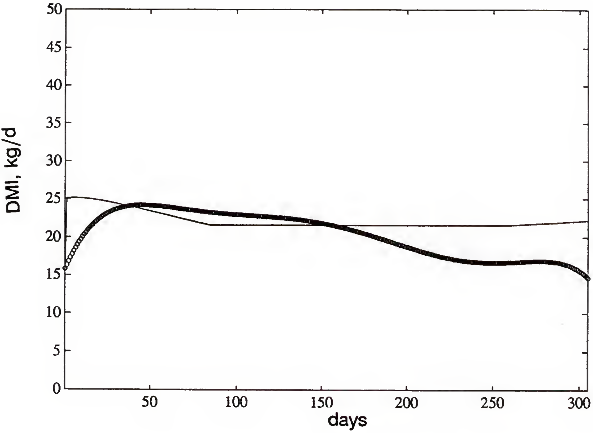

Figure 4-34. Plots of actual daily DMI (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

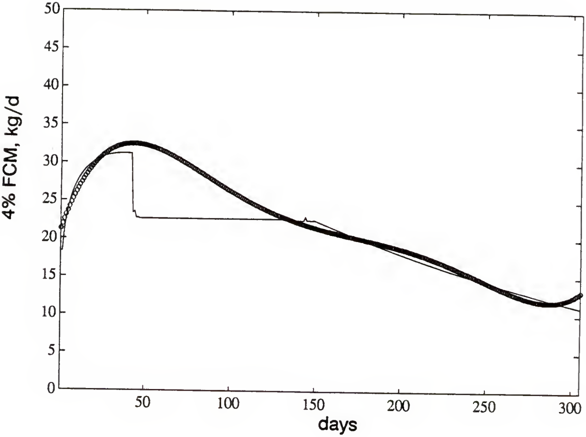

Figure 4-35. Plots of actual daily 4% FCM (kg/d) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily 4% FCM (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

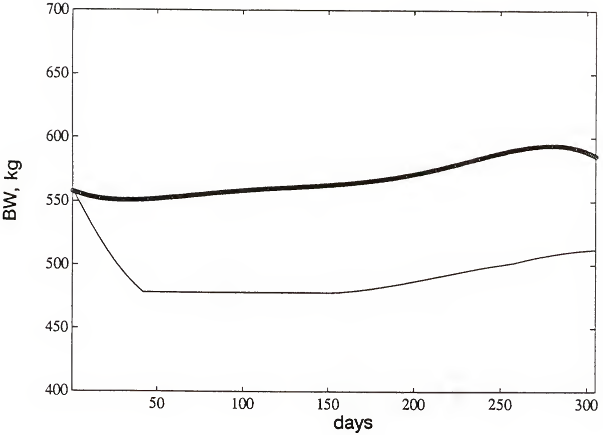

Figure 4-36. Plots of actual daily BW (kg) with 1.709, 1.685 and 1.663 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 305, respectively (dark line) vs. predicted daily BW (kg) with 1.1 Mcal/kg of DM throughout lactation (light line) for the Kodak data set.

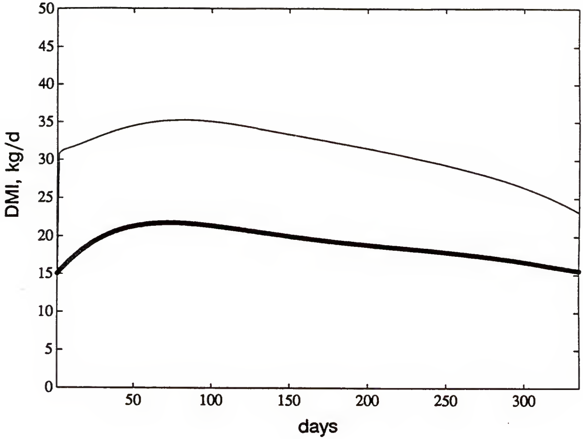

Figure 4-37. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit of DMI.

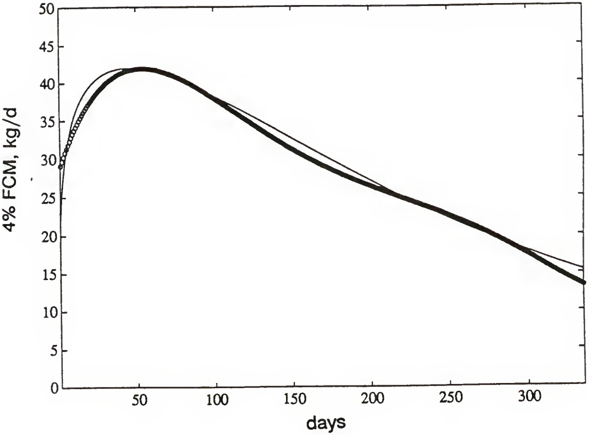

Figure 4-38. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit of DMI.

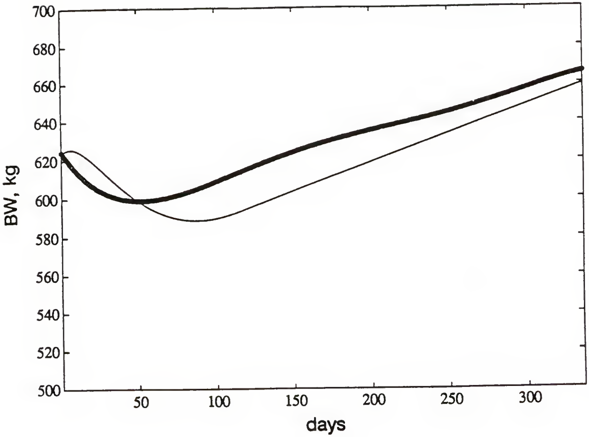

Figure 4-39. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit of DMI .

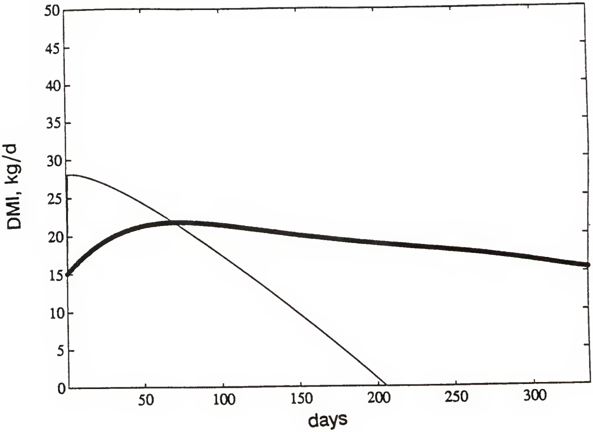

Figure 4-40. Plots of actual daily DMI (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily DMI (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit for maximum BW loss.

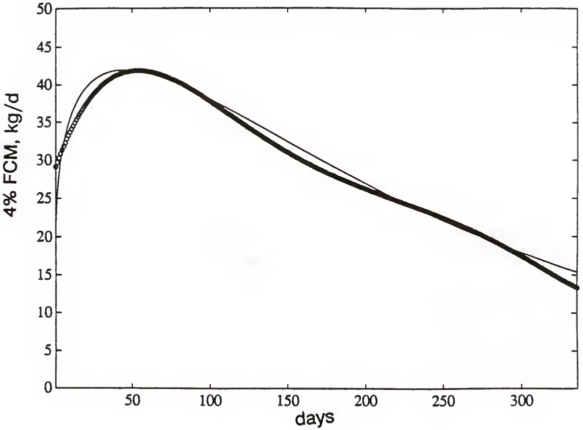

Figure 4-41. Plots of actual daily 4% FCM (kg/d) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. fitted daily 4% FCM (kg/d) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit for maximum BW loss.

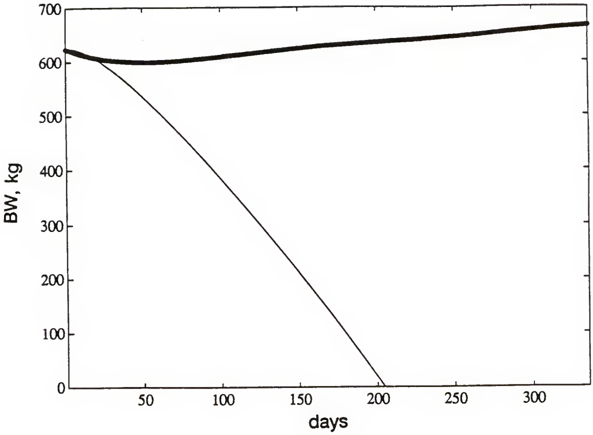

Figure 4-42. Plots of actual daily BW (kg) with 1.69, 1.55 and 1.52 Mcal/kg of DM for d 1 to 112, 113 to 224 and 225 through 336, respectively (dark line) vs. predicted daily BW (kg) with 1.1 Mcal/kg of DM throughout lactation (light line) for the medium NH data set with no imposed limit for maximum BW loss.

Summary and Conclusions

The model's capacity to predict production responses to proposed changes in dietary NEL concentrations was evaluated in a qualitative manner. All data sets described in detail in Chapter III were used in this evaluation. The DMI, 4% FCM and BW responses to changes in energy concentration of the diet over lactation were represented graphically and compared with the corresponding actual response curves generated with the original NEL concentrations of the diets of each data set.

The predicted responses of the model to reductions in the energy concentration of the diet followed the patterns that would be expected in the real system. It is likely that the reduction of MY due to a low NEL concentration of the diet is a gradual response rather than an abrupt one as predicted in some instances by the model in this chapter. However, because no information about the mechanism involved in the temporal pattern, or magnitude of this response is available currently, it was presumed that changes in response variables due to changes in input variables such as NEL concentration of the diet occurred simultaneously.

The model predicted an increase in DMI to compensate for the lower NEL concentration of the diet. When the maximum limit of DMI was reached, the model predicted use of the BER to meet the energy requirements for maintenance, pregnancy and lactation. Until this point, ES was unaltered (zero energy balance). Thereafter, milk production was predicted to decrease according to the energy deficit.

CHAPTER V
QUANTITATIVE EVALUATION OF THE MODEL

Introduction

Cows and their respective potentials, available feed and the environment are interacting components of a system. The outcomes of such interactions are productive responses. Productive responses such as MY, DMI and BW and their rates of change over the course of a lactation cycle have significant practical implications in a dairy enterprise. Quantitative prediction of these productive responses is therefore, essential.

As early as 1942, Jensen et al. (1942) described the positive relationship between feed intake and MY. They demonstrated that milk production increased as feed intake increased, but at a progressively diminishing rate. Restriction of feed intake, whether arising inherently from chemical and physical characteristics of the feed or the anatomy and physiology of the cow, represent the most obvious practical limitations on milk production (Conrad et al.,1964). The extent and rate of BW change during lactation may affect MY, ES, health and reproductive status (Garnsworthy, 1988).

Mathematical models that describe the existing dynamic relationships among BW gain or loss, feed intake and milk production may improve the management of body reserves and contribute to more efficient milk production.

Over the last three decades, much research has focused on the prediction of DMI (Brown et al., 1977; McCullough, 1981; Chase and Sniffen, 1985; Kertz et al., 1991; Rayburn and Fox, 1993) and DMI regulation (Conrad et al., 1964; Forbes, 1977; Mertens, 1987; Williams et al.1989a). However, not much research has been applied to building mathematical models to predict production responses and their interrelationships in dairy cattle. In previous chapters a bioenergetic model for the lactating, pregnant adult cow was presented and was shown to provide reasonable responses when challenged with different dietary energy concentrations.

The purpose of the study presented here was to test the model by evaluating its ability to quantitatively predict the outcomes of a "real system." This evaluation is based on the degree of conformity between predicted and observed responses and is known as the test of the "goodness of fit" (Naylor and Finger, 1967). Because dynamic simulation models have time as a driving variable and produce output in time series, an important evaluation technique is to plot results against time (Sorensen, 1990).

Materials and Methods

Experimental Data Sets

The NH (medium, high and low) and Kodak data sets, described in detail in Chapter III, were used to evaluate the model developed with the Monsanto data set in a quantitative manner. The quantitative evaluation of the model was performed by measuring the degree to which the model and actual outputs were similar in magnitude.

Analytical Procedure

To measure the degree to which actual and predicted outputs were quantitatively similar, $MSPE_e$, MPE_e and relative error (r.e. is the MPE expressed as a percentage of the mean actual output) were calculated. The set of parameters (b_i) estimated for the Monsanto data set (Table 3-8) was used to evaluate the model with independent data sets mentioned above.

Results and Discussion

The qualitative evaluation of the model performed in Chapter IV showed that changing the dietary NEL concentration (from original values to 1.5; 1.35; 1.25 and 1.1 Mcal/kg of DM) affected predicted responses. The differences between the original NEL concentration and the reduced value were greater than the difference in NEL concentrations among data sets. Therefore, differences in NEL concentration among the data sets used in the quantitative evaluation of the model were not expected to cause changes in predicted responses (see page 111 for original actual energy concentration of the diets).

When the model was evaluated with the medium NH data set, DMI responses were predicted quite well with a slight over-prediction during the first few days of lactation and under-prediction in late lactation (Figure 5-1). The values of $MSPE_e$, MPE_e and r.e. with respect to the mean (19.06 kg/d) for DMI (for the whole lactation) were 1.96 kg^2/d, 1.4 kg/d and 7.34%, respectively (Table 5-1). Factors such as environment and management are known to affect DMI (Roseler, 1994). In addition, the environmental and management conditions most likely differ among data sets. This could explain in part the differences observed between actual and predicted DMI.

A close agreement between actual and fitted 4% FCM production was observed (Figure 5-2). The milk production potential was maximal, which was represented in the model by Wood's equation (Wood, 1967). The parameters of Wood's equation were calculated for each data set. This explains the similarity between actual and predicted responses. The $MSPE_e$, MPE_e and r.e. with respect to the mean (29.23 kg/d) were .92 kg^2/d, .96 kg/d and 3.28%, respectively (Table 5-1).

Table 5-1. Values of $MSPE_e$, MPE_e and r.e. for DMI, BW and FCM used to quantify the model's predictive accuracy with independent data sets.

	$MSPE_e$ (kg^2/d or kg^2)[a]	MPE_e (kg/d or kg)[b]	r.e. (%)
Medium NH			
DMI	1.96	1.40	7.34
BW	233.89	15.29	2.43
FCM	.92	.96	3.28
High NH			
DMI	1.51	1.23	6.43
BW	226.95	15.06	2.40
FCM	.53	.73	2.44
Low NH			
DMI	2.48	1.57	8.60
BW	448.18	21.17	3.38
FCM	.50	.71	2.62
Kodak			
DMI	20.60	4.54	22.30
BW	1434.94	37.88	6.33
FCM	.60	.78	3.56

[a] $MSPE_e$ for DMI and 4% FCM, kg^2/d and for BW, kg^2.
[b] MPE_e for DMI and 4% FCM, kg/d and for BW, kg.

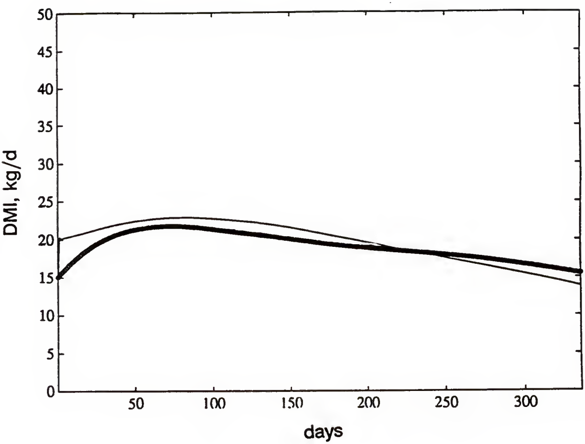

Figure 5-1. Plots of actual (dark line) and predicted (light line) daily DMI (kg/d) for medium NH data set when evaluated with the parameters estimated with the Monsanto data set.

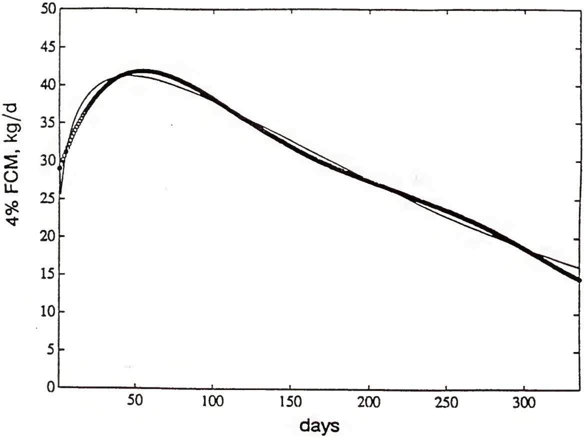

Figure 5-2. Plots of actual (dark line) and fitted (light line) daily 4% FCM (kg/d) for medium NH data set when evaluated with the parameters estimated with the Monsanto data set.

When compared with actual BW, the model over-predicted BW in early and late lactation (Figure 5-3). The over-prediction of BW in early lactation most probably resulted from the over-prediction of DMI during the same period. Due to the over-prediction of BW in early lactation the predicted loss of BW was shifted in time with respect to the actual BW (Figure 5-3). The $MSPE_e$, MPE_e and r.e. with respect to the mean BW (628.60 kg) over the entire lactation were 233.89 kg^2, 15.29 kg and 2.43%, respectively (Table 5-1).

The model's prediction of DMI, FCM and BW compared with the actual responses for the high NH data set are shown in Figures 5-4, 5-5 and 5-6, respectively. The quantitative evaluation of the model is given by the values of $MSPE_e$, MPE_e, and r.e. for DMI, FCM and BW (Table 5-1). These values were lower than those obtained with the medium NH data set (Table 5-1), indicating that the model's predictive ability was slightly better with the high than with the medium NH data sets. The mean values over the entire lactation for DMI, BW and FCM are 19.12 kg/d, 628.72 kg and 29.9 kg/d, respectively.

The predicted DMI, FCM production and BW responses for the low NH data set followed approximately the same patterns as those prediction responses corresponding to medium and high NH data sets (Figure 5-7, 5-8, 5-9). This behavior should be expected because the experimental conditions were similar for the three data sets. Also NEL of the diets were not vastly different; 1.72, 1.58 and 1.57 Mcal/kg of DM; 1.69, 1.55 and 1.52 Mcal/kg of DM; and 1.66, 1.53 and 1.51 Mcal/kg of DM, between d 1 to 112, 113 to 224 and 225 through the end of

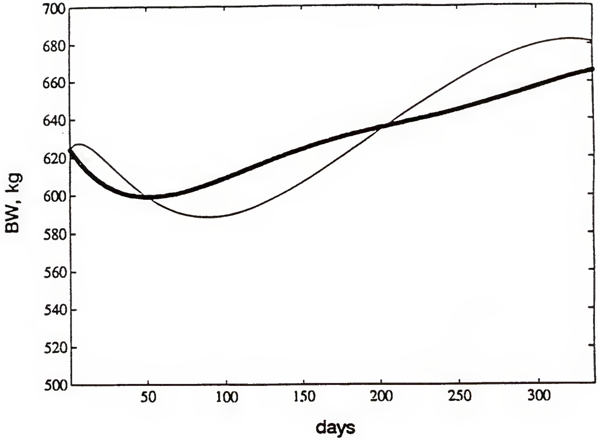

Figure 5-3. Plots of actual (dark line) and predicted (light line) daily BW (kg) for medium NH data set when evaluated with the parameters estimated with the Monsanto data set.

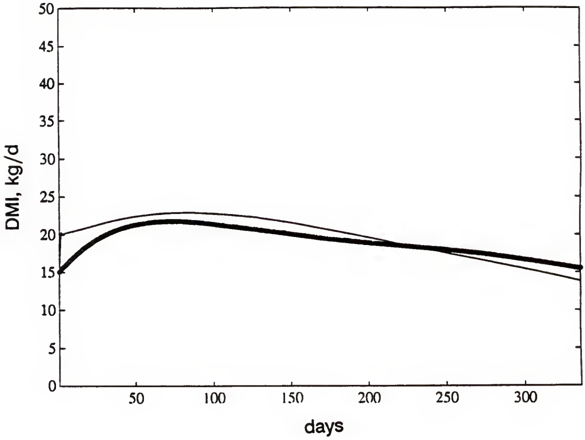

Figure 5-4. Plots of actual (dark line) and predicted (light line) daily DMI (kg/d) for high NH data set when evaluated with the parameters estimated with the Monsanto data set. The predicted response shown here is very similar to the predicted response shown in Figure 5-1; however, the equation of the two predicted responses differ slightly.

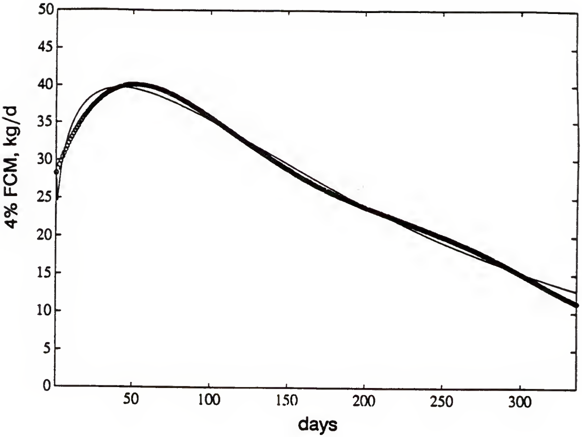

Figure 5-5. Plots of actual (dark line) and fitted (light line) daily 4% FCM (kg/d) for high NH data set when evaluated with the parameters estimated with the Monsanto data set.

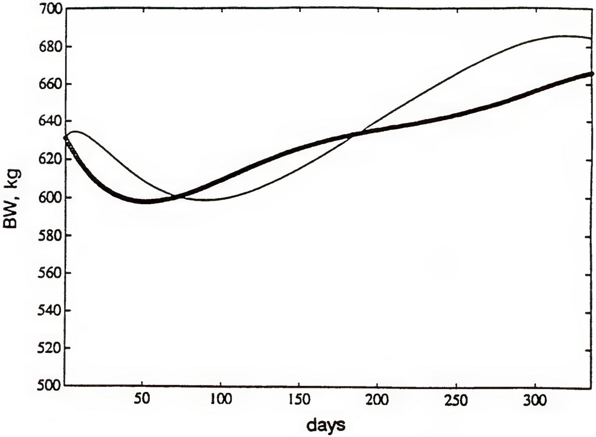

Figure 5-6. Plots of actual (dark line) and predicted (light line) daily BW (kg) for high NH data set when evaluated with the parameters estimated with the Monsanto data set.

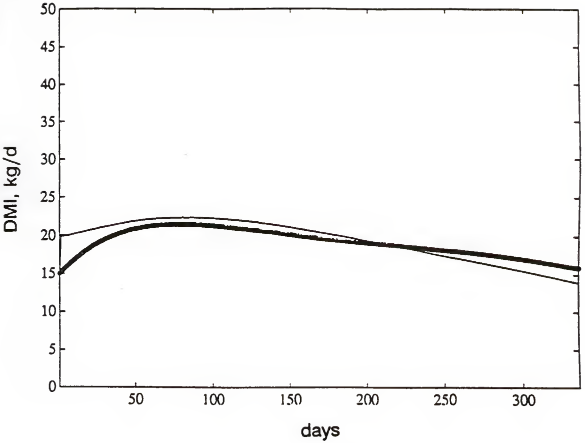

Figure 5-7. Plots of actual (dark line) and fitted (light line) daily DMI (kg/d) for low NH data set when evaluated with the parameters estimated with the Monsanto data set.

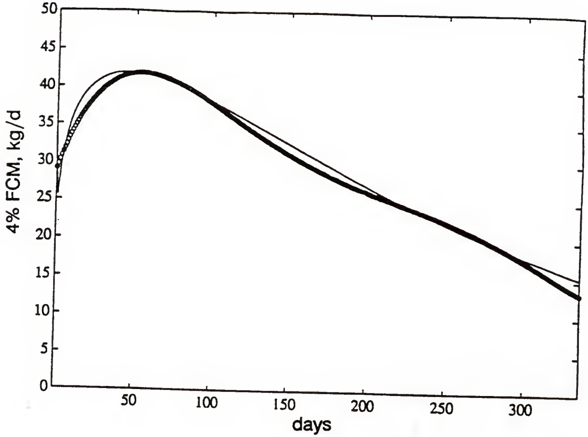

Figure 5-8. Plots of actual (dark line) and fitted (light line) daily 4% FCM (kg/d) for low NH data set when evaluated with the parameters estimated with the Monsanto data set.

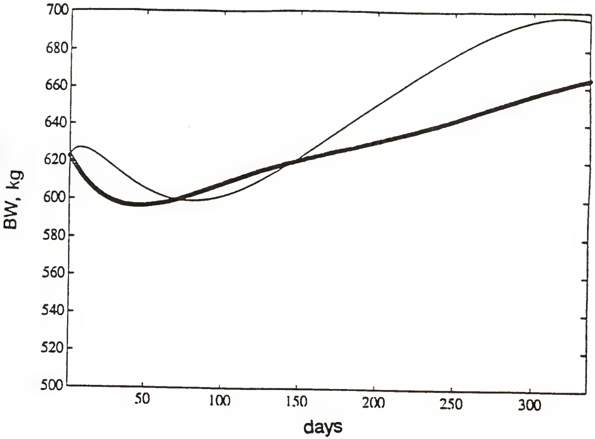

Figure 5-9. Plots of actual (dark line) and predicted (light line) daily BW (kg) for low NH data set when evaluated with the parameters estimated with the Monsanto data set.

lactation, respectively, for high, medium and low NH data set, respectively. The purpose of dividing the NH set into three subsets was to quantify the model's predictive ability when the dietary energy concentrations and the initial values of DMI, BW and FCM differed. The quantitative indicators of the model's predictive accuracy are presented in Table 5-1. The mean values for DMI, FCM and BW were 18.2 kg/d, 27.06 kg/d and 625.81 kg, respectively.

Body weight, DMI and FCM are interrelated closely. Factors that affect one response variable indirectly affect the other response variables. Environmental conditions, bunk management and herd management are some of these factors. The differences in actual responses observed among data sets (Chapter III) can be explained partly by differences in environmental and management conditions. Based on the differences between the Monsanto and NH data sets and the fact that none of these factors were included in the model, the predictive ability of the model with these three data sets was good; comparable to other reports in literature.

The poorest predictive performance of the model was with the Kodak data set (Figures 5-10, 5-11 and 5-12). The values of $MSPE_e$, MPE_e and r.e. with respect to the mean (20.3 kg/d) for DMI were 20.60 kg^2/d, 4.54 kg/d and 22.30%, respectively. For BW, $MSPE_e$, MPE_e and r.e with respect to the mean (528.22 kg) were 1234.94 kg^2/d, 37.88 kg/d and 6.33%, respectively (Table 5-1). The DMI response was under-predicted throughout lactation, whereas BW was over-predicted throughout lactation and at an increasing rate. These differences between actual and predicted responses can be related to the differences in actual DMI and BW that exist between the Kodak and the Monsanto data sets. The latter being the data set used to develop the model. Monsanto's lower DMI and higher BW would explain the observed under-prediction of DMI and the over-prediction of BW. As expected, FCM (equivalent to the cows' potential) was fitted accurately as shown by the low values of $MSPE_e$ (.6 kg^2/d), MPE_e (.78 kg/d) and r.e. (3.56%) with respect to the mean FCM (21.88 kg/d).

Bywater (1984) tested his complete feed intake and digestion model against data from seven individual Jersey lactations. The mean r.e. of prediction for DMI was used as measure of the prediction error. This author reported a mean for all lactations of 14.1%, with a range between 11.8 and 17.2%.

The evaluation of the model of Bruce et al. (1984) was performed by calculating the mean deviation (predicted - actual) for MY and BW (Broadbent et al. 1984). The DMI was an input of the model. For MY, the statistical analysis was performed for 166 whole lactations, whereas for BW the difference of predicted and actual was calculated separately for each observation occurring at approximately, wk 14, 26 and 38 of lactation. There was substantial agreement between the mean predicted and actual values for MY, with a mean deviation of .04 MJ of ME/d and SE of the mean of .485 MJ of ME/d. The predicted and actual BW showed close agreement in early lactation (mean deviation: 1.0 kg, SE: 1.76 kg), but BW was over-predicted in mid (mean deviation: 14.3 kg and SE: 2.23 kg) and late lactation (mean deviation: 31.2 kg and SE: 2.71 kg). Data from

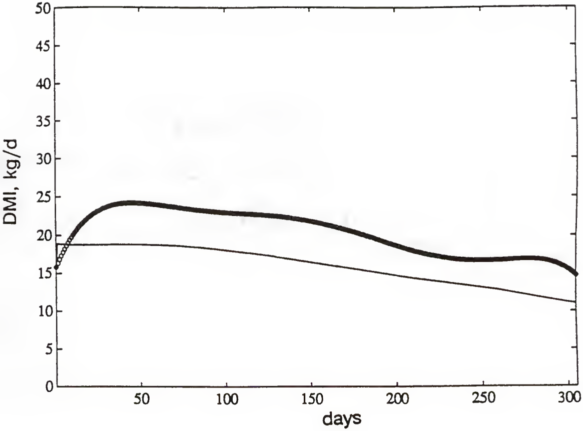

Figure 5-10. Plots of actual (dark line) and predicted (light line) daily DMI (kg/d) for Kodak data set when evaluated with the parameters estimated with the Monsanto data set.

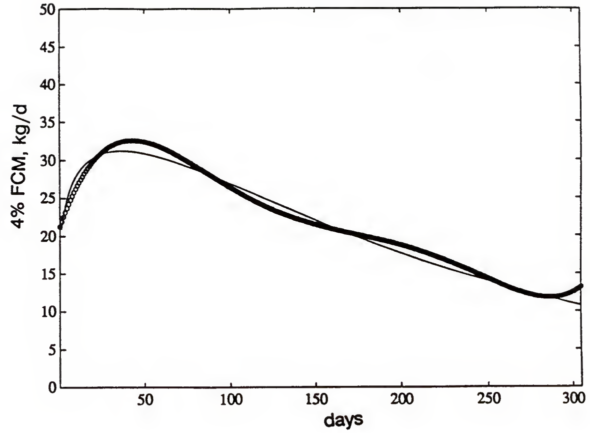

Figure 5-11. Plots of actual (dark line) and fitted (light line) daily 4% FCM (kg/d) for Kodak data set when evaluated with the parameters estimated with the Monsanto data set.

a complete lactational cycle showed an over-prediction of post-calving BW of 50.7 kg. Williams et al. (1989a) compared predicted results from his model of feed intake, lactation responses and BW changes with experimental data which was collected over 44 wk of lactation and included different feeding systems. These researches reported little differences between the observed and predicted lactation yields and BW changes. However, the limited amount of data reported by these researches was not enough to compare the prediction accuracy of their model with other models.

Roseler (1994) tested the prediction accuracy of the DMI equations developed by Kertz et al. (1991), NRC (1989), Weiss (1991) and Roseler (1994) with six independent data sets (for multiparous cows). The measures of evaluation accuracy were based upon the overall MSPE values.

Accuracy of the DMI equations evaluated by Roseler (1994) varied widely depending on the data set used in the evaluation. The MSPE values for Kertz et al. (1991) equation ranged between 7.1 and 60.8 kg^2/d, with a mean MSPE of 31.62 kg^2/d. The MSPE values corresponding to NRC (1989) DMI equation varied from 4.9 to 61.9 kg^2/d, with an average value of 29.95 kg^2/d. The MSPE for Weiss (1991) equation varied from 2.8 to 74.1 kg^2/d, with an average value of 38.18 kg^2/d. The MSPE of the simplified DMI prediction equations developed by Roseler (1994) ranged between 1.5 and 22.4 kg^2/d, with a mean value of 8.6 kg^2/d. The MSPE values calculated for the comprehensive DMI prediction equation developed by Roseler (1994) varied from .37 to 15.0 kg^2/d, with an average MSPE of 4.02 kg^2/d.

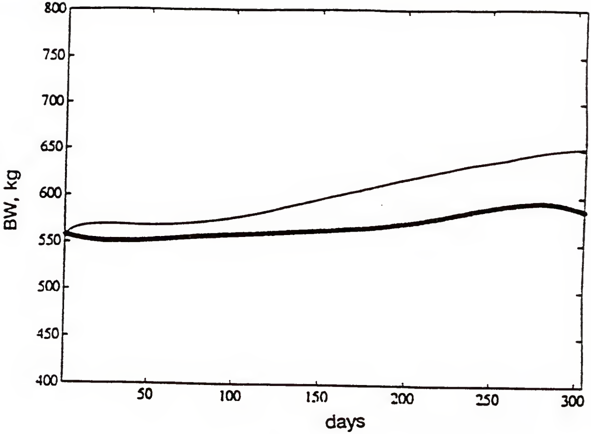

Figure 5-12. Plots of actual (dark line) and4 model predicted (light line) daily BW (kg) for Kodak data set when evaluated with the parameters estimated with the Monsanto data set.

More independent data sets are needed to assess the robustness of the model developed in this study (Chapter III). However, based on the results of the evaluation studies of Bywater (1984) and Roseler (1994) and those described in this chapter, the accuracy of the model to predict DMI is comparable to that of Roseler's simplified equation which ranked second in his study. Furthermore, the MPE for BW and FCM of the model were lower than 7% of the respective mean actual values. These values can be considered satisfactorily low and indicative of the model's acceptable predictive capacity.

Summary and Conclusions

A quantitative evaluation of the model developed with the Monsanto data set was carried out by measuring the degree to which the predicted and actual outputs were similar in magnitude. The $MSPE_e$, MPE_e and r.e. were calculated to measure the model's ability to predict DMI, FCM and BW.

The best predictive performance of the model developed with the Monsanto data set was with the high NH data set. The calculated MPE_e for DMI, FCM and BW were 1.23 kg/d, .73 kg/d and 15.06 kg, respectively. Slight differences in the predictive ability of the model were observed when using the medium and low NH data sets (Table 5-1). Quantitatively, when using the parameters estimated for the Monsanto data set, the poorest performance of the model was with the Kodak data set. The MPE_e for DMI, FCM yield and BW were 4.54 kg/d, .78 kg/d and 37.88 kg, respectively. The differences between actual and predicted DMI and BW may have been related to the differences in actual DMI and BW existing between the Monsanto and Kodak data sets.

The $MSPE_e$ for DMI calculated in this study compared well with those obtained in other evaluation studies (Bywater, 1984; Roseler, 1994). In addition, the calculated MPE_e for FCM production and BW were under 7% of the mean observed values. Overall, the model's predictive capacity was considered reasonable.

CHAPTER VI
SUMMARY, CONCLUSIONS AND FUTURE RESEARCH NEEDS

A dynamic model that quantitatively represented the energy transactions among maintenance, lactation, gestation and body reserves, and thus defined the ES of the multiparous dairy cow throughout lactation was developed in this study. Understanding and quantifying the energy flow in a temporal and rate specific manner is essential in order to make decisions and control effectively the energy transactions of cows, and potentially the physical and economic performance of the dairy business. Feeding cows to achieve optimum results requires the dairy producer to be able to predict how IE responds to milk production (or vice versa), and how IE affects body reserves status throughout lactation and the dry period.

The model developed is empirical because it is based on empirical data sets, observation and experience, and not necessarily on preconceived, known or tested biological theories or mechanisms at lower levels of aggregation (e.g., cellular, tissue or organ systems). Equations that best described responses of DMI, FCM and BW from experimental data at a whole cow level were constructed. In construction of the model, it was assumed that energy requirements for maintenance and pregnancy had priority in the use of IE over lactation and BER, and that lactation had priority in the use of the remaining IE over BER. This assumption was used to calculate the amount of available energy for milk production.

Intake energy at day t of lactation was assumed to be driven by MTE, PGE and MIE requirements of the previous day as well as by the energy requirements of the cow to attain a TBW. The TBW was defined as the BW of the cow on the day prior to calving because this theoretically represents the maximum BW for any lactational cycle of a mature cow and it includes the BW gain associated with pregnancy. Thus the IE equation was defined as:

$$IE_t = b_1\ [(TBW\text{-}BW_{(t\text{-}1)})/TBW] + b_2\ MTE_{(t\text{-}1)} + b_3\ MIE_{(t\text{-}1)} + b_4\ PGE_{(t\text{-}1)}.$$

The FCM equation was based on the concept of a milk production potential represented by Wood's equation (Wood, 1967) and the influence of the NEL concentration of the diet, BER, and energy requirements on milk production. It was assumed that if the available energy (AE) for FCM production ($IE_{(t-1)} - MTE_{(t-1)} - PGE_{(t-1)}$ - BER) was greater than or equal to the required energy (RE) to produce milk, the cow produced milk to its potential, and used any excess energy for BW gain. However, if the AE was less than RE, the potential MY was reduced according to the availability of energy:

$$FCM_t = [\text{FCM potential}]\ AE/RE$$

To calculate the BW, a differential equation was used. For the construction of this equation it was assumed that changes in BW result from energy deficits or surpluses:

$$\frac{dBW_t}{dt} = [IE_t - RE_t]\ /\ \text{energy requirement for BW change}$$

Very different conditions seemed to prevail among data sets as evidenced by the differences in actual BW, DMI and FCM responses over time (Figures 3-1, 3-2 and 3-3). For this reason, the model's parameter estimates (b_i) were estimated separately for each data set (Table 3-8). The optimization technique (FMINS) and the simultaneous solution of the equations were implemented with Matlab (1993). To solve the differential equation ODE 23, an automatic step size integration method was implemented. To quantify the accuracy of the model in fitting the experimental data, the MSE_m was calculated. The $MSPE_e$ and MPE_e were calculated for each independent equation of the model to identify and quantify the accuracy in fitting the data of each component of the model.

No biological meaning can be assigned to the energy requirement estimates (b_1, b_2, b_3 and b_4) obtained using FMINS. Because this technique solved the equations of the model simultaneously, the values of the resulting parameters were not independent from each other. The parameters of the model were interpreted as being the numerical combination that provided the minimum sum of squares of the actual values and those predicted by the model corresponding to DMI, FCM and BW.

Overall, the model's ability to predict experimental data was acceptable as evidenced by the MPE_m, $MSPE_e$ and MPE_e values (Table 3-9) and the graphic representations of predicted and actual responses (Figures 3-4 through 3-12).

The purpose of the qualitative evaluation of the model presented in Chapter IV was to test the model's capacity to predict production responses to imposed changes in dietary energy concentrations. Limits on maximum DMI (4 and 4.5%

BW) and BW loss (80 kg) from calving to nadir were imposed on the model. The initial dietary NEL concentrations of each data set were successively reduced to 1.5, 1.35, 1.25 and 1.1 Mcal/kg of DM. The DMI, FCM and BW responses to changes in NEL concentration were represented graphically (Figures 4-1 through 4-36). Response curves were compared with the corresponding actual curves generated with the original NEL concentrations of diets as reported in separate experiments.

The predicted responses of the model to changes in dietary NEL concentrations followed patterns that might be expected in the real system. The model predicted an increase in DMI as a first attempt to maintain BW and MY as set originally by the MY potential. Once the imposed DMI limit was reached, the model predicted the use of BER to a maximum. Until this point the ES of the cow remained unchanged. Thereafter, MY was predicted to decrease according to the energy deficit.

In Chapter V the model was evaluated quantitatively. The evaluation was based on the degree of agreement between predicted and actual responses as measured by the $MSPE_e$, MPE_e and r.e.. In Chapter III, the NH data which comprised a variety of dietary treatments, was split into three subsets (high, medium and low NH) according to NEL concentrations of the diets. The three NH and the Kodak data sets were used to evaluate the model developed with the Monsanto data set. Different data sets imply different values of DMI, FCM and BW for the first day of lactation, and therefore different conditions under which the model's predictive capacity can be evaluated.

When using the parameters estimated with the Monsanto data set, the best predictive performance of the model was with the high NH data set (Figures 5-4 through 5-6). The MPE_e for DMI, FCM yield and BW were 1.23 kg/d, .73 kg/d and 15.06 kg, respectively (Table 5-1). The model's predictive ability showed only slight differences when evaluated with the medium and low NH data sets (Figures 5-1 through 5-3 and Figures 5-7 through 5-9). The poorest performance of the model was with the Kodak data set (Figures 5-10 through 5-12, respectively). The MPE_e for DMI, FCM production and BW were 4.54 kg/d, .78 kg/d and 37.88 kg, respectively. The differences between actual and predicted outcomes were related to differences in actual DMI and BW existing in actual responses between the Monsanto (developmental data set) and the Kodak data sets. Monsanto's lower DMI and higher BW would explain the observed under-prediction of DMI and the over-prediction of BW.

The $MSPE_e$ for DMI calculated in this study compared reasonably well with those reported previously (Roseler, 1994; Bywater, 1984). Furthermore, the calculated MPE_e for FCM and BW were less than 7% of the mean observed value. In this study, the model's predictive ability was considered satisfactory. Although these results do not guarantee that the model also will behave acceptably under other conditions, the model developed with the addition of the necessary economic inputs potentially could be used as a practical management tool. For example, it could be useful in the development of nutritional strategies for the entire lactation by managing the energy budget of cows to maximize biological efficiency and economic profits. It could also be used to determine the dietary energy costs associated with production at any stage of lactation, and to predict energy and feed requirements to aid in the planning of economical feed production, purchasing and contracting.

Throughout this dissertation the effect of changing the energy concentration of the diet, the initial values of DMI, 4% FCM and BW on the model's ability to predict outcomes were evaluated. From a practical point of view, in the future it would be desirable to evaluate the effects of changing the day of conception, the fat content of the milk or even reducing the potential MY on the model's behavior. Also it would be necessary to evaluate the behavioral response of the model with different feed and herd management practices. These evaluations will determine what modifications, if any, should be made to the current model.

An equation to quantify energy requirements for growth needs to be incorporated into the model in order to evaluate the model's predictive capacity with first and second parity cows. To make this addition, the partition of energy among the various metabolic processes would need to be redefined. The incorporation of economic variables potentially could be considered as an additional development step before testing this model as a practical management tool.

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BIOGRAPHICAL SKETCH

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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